Enhancing the Quality of U.S. Grain for International Trade

Volume II -- Background Papers

Part B (1st section): Technologies Affecting Quality

1. Effect of Harvesting Technologies on Corn and Soybean Quality
2. Wheat Quality as Influenced by Harvesting Machinery
3. Handling and Storage of Wheat: An Assessment of Current Technology
4. The Interaction of Corn and Soybean Quality with Grain Storage
5. Cleaning and Blending of Corn and Soybeans
6. Grain Drying Technology

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Paper No.

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Background Paper No. 1

Effect of Harvesting Technologies on Corn and Soybean Quality

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Office of Technology Assessment
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EFFECT OF HARVESTING TECHNOLOGY
ON CORN AND SOYBEAN QUALITY

INTRODUCTION

Harvesting can be defined as the process by which the high-valued parts (grains and oilseeds) are removed from a plant, gathered, and physically removed from a field. With combines, the crop is threshed to remove kernels from crop material, separated, and cleaned. For purposes of this particular study, harvesting will refer to combine harvesting and harvesting technologies will pertain primarily to corn (Zea mays L.) and soybeans (Glycine max L.). (Another portion of the overall Office of Technology Assessment study will cover the effects of combine harvesting on wheat quality.) This study will focus on the following: a) an historical perspective on the evolution of harvesting machines and methods and current statistical trends on numbers of combines; b) components and performance parameters of combines; c) effects of harvesting on grain quality; d) emerging technologies and their probable effects on grain quality; and e) analysis of current harvesting technology and costs for providing grain of desirable quality for various end-uses.

HISTORICAL PERSPECTIVE

One of the most important events in harvesting technology occurred in 1831 when Cyrus Hall McCormick tested his first reaper.

Later, in 1834, he patented the reaper at about the same time that Obed Hussey from Ohio built and claimed to have also invented the reaper, Quick and Buchele (1978). Later, McCormick moved to Chicago and was first to mass produce reapers. Prior to this time, however, winnowing fans were used in China in 1313 for separating grain from chaff. Later in 1758 a threshing drum was used by a Scotsman, named Leckie. Various modifications were made to the threshing drum, but by combining the principle of reaping and threshing into one machine the first workable combine was developed by Hiram Moore and John Hascall in Michigan and was patented in 1836, Quick and Buchele (1978). These combines were improved over the years, but were primarily used for small grains. Another major advancement occurred in 1953 when Hopkins and Pickard (1953) at the University of Illinois investigated adapting the combine to harvest corn. At the time, advantages cited for corn combining were to reduce corn-picker-related farm accidents and harvest losses. Historically, the switch from picking corn in the ear to combine shelling/harvesting increased the efficiency of corn production, but also created new problems resulting from the need to artificially dry corn.

In recent years, several combine manufacturers have introduced rotary combines. In 1975 Sperry New Holland[1] introduced their Twin

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[1] Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name, proprietary product or specific equipment does not constitute a guarantee or warranty by the author, the University of Illinois, or the Office of Technology Assessment and does not imply approval of the named product to the exclusion of other products that may be suitable.

Rotor combine (Figure 1), followed in 1977 by International Harvester with a single rotor combine (Figure 2), Deutz-Allis (formerly Allis-Chalmers) in 1978 with a single transverse rotor, and White in 1979 with a single rotor combine. Reasons cited by manufacturers for the change were the ability to use centrifugal separation instead of straw walkers resulting in fewer moving parts and reduced grain crackage, DePauw et al. (1977). In spite of all the publicity accompanying the introduction of rotary combines, the technology for centrifugal threshing and separating had been investigated by Lamp and Buchele (1960) and concluded to be feasible some 15 years earlier. Their study was limited to corn, soybeans, and wheat and they did encounter some difficulty in centrifugally threshing wheat at very high moistures (above 40 %). Quick (1978) also reported that rotary threshing devices had problems of straw wrapping and higher power requirements in long damp straw. Thus, uncertainty of performance at very high moistures and the further research needed for other crops such as rice and other small grains were factors contributing to the time needed for commercial development of rotary combines.

Over the past 25 years, U.S. corn acreage harvested went from 71,422,000 in 1960 to 75,134,000 in 1985, Table 1. Acreage during that period reached a low of 51,483,000 in 1983. Over the same period, production went from 3.91 billion bushels in 1960 to 8.87 billion bushels in 1985. Average yield has climbed steadily from a low of 55 bu/A in 1960 to a high of 118 bu/A in 1985.

United States soybean acreage harvested went from a low of 23,655,000 in 1960 to 61,584,000 in 1985, Table 2. The highest acreage occurred in 1979 with 70,343,000 acres. U.S. soybean production went from a low of 0.55 billion bushels in 1960 to a high of 2.26 billion bushels in 1979. Average yields increased from 23 bu/A in 1964 to a high of 34 bu/A in 1985.

Numbers of combines sold annually to U.S. farmers have decreased from a high of 42,276 units in 1967 to a low of 7,681 in 1986, Table 3. Thus, there has been a significant trend toward fewer combines. To harvest more soybean acres while maintaining approximately the same number of corn acres with fewer machines, it is obvious that the combine capacities must have increased. Combine capacities are partially defined in terms of classes. A class designation is used by the Farm and Industrial Equipment Institute (FIEI) to place combine models into competitive groups based on combine capacity and cost. A class 1 combine has the lowest harvesting capacity in bu/hr whereas a class 6 machine has the highest capacity. In 1964 class 2 combines were the most common size sold. By 1986, class 5 machines were the most common, representing a large increase in capacity and cost.

The shift from ear corn harvesting to combine shelling is most evident from Table 4. The number of corn pickers sold annually in the U.S. decreased from 17,078 in 1965 to 6,673 units in 1974. After 1974, sales of cornpickers were so low that no data was available. Presently, the seedcorn industry is a prime user of cornpickers, primarily to preserve high seed germinability.

Since not all combines sold in the U.S. are used for corn, the ratio of cornheads sold to the total number of self-propelled combines was computed. Since most row-crop headers are used with self-propelled combines, pull-type combines were not included in the calculation, Table 5. The percentage of combines with cornheads has gone from a low of 54 % in 1983 to a high of 81 % in 1975. The lowest sales of cornheads occurred in 1983 when corn acreage dropped to 51 million acres. The small number of cornheads sold in 1983 was probably due to the PIK farm program.

While increases in combine capacities have been significant, any further increases in capacity will be constrained by physical size limitations. Header widths of 30 feet are the maximum presently available and are not uncommon. These header widths in many cases, exceed road widths which makes road transport difficult without first removing the header from the combine. Combine tread widths of class 6 combines reach 12 ft. 1 in. with tires mounted for field use. For transport from the factory, rims must be turned fully inward to fit on semi-trucks. Thus, combine width is now and will become a greater limiting factor for future increases in combine size. Presently, the trend has been toward fewer numbers of combines but with higher percentages of the combines in the larger sizes.

Presently there are seven companies that manufacture nearly all of the combines used in the United States, Table 6. Based on sales data compiled by the Farm and Industrial Equipment Institute (FIEI), the seven companies manufacturing combines are Case-IH, Claas, Deere and Company, Deutz-Allis, Ford New Holland, Massey Ferguson, and New Idea. From these seven manufacturers, 42 models are produced. Of these 42 models, 14 are classified as having rotary threshing/separating mechanisms, Implement and Tractor (1987). Further discussion of rotary and conventional threshing will follow.

To provide a degree of commonality in determining dimensions and capacities of combines, three standards have been developed by the American Society of Agricultural Engineers (ASAE). Standards include: a) S343.1, Terminology for combines and grain harvesting; b) S396, Combine capacity test procedure; and c) S312.1 Capacity designations for combine grain tank systems, ASAE (1987). In addition, there are International Standards Organization (ISO) standards which are used worldwide.

COMPONENTS AND PERFORMANCE PARAMETERS

Further description of the effects of combines on the quality of harvested corn and soybeans requires a basic knowledge of various combine components. It is necessary to maintain a total perspective of what a combine is expected to do because of the interdependency among components and performance parameters. For example, increases in cleanliness of grain in the tank may occur at the expense of higher grain loss from the combine. Thus, there are always many tradeoffs among combine performance parameters.

Components

The six major components of a combine include: a) the gathering unit or header; b) the feeding unit; c) threshing unit; d) separating unit; e) cleaning unit; and f) grain transfer unit.

The gathering unit or header can be either a platform or row-crop unit. Platforms typically use a cutterbar to sever plant stems. A reel assists in delivery of crop material into the platform where a large diameter auger carries material to the center of the platform for conveying by the feeding mechanism into the threshing unit. For corn headers, snapping rolls strip the ear from the corn stalk so that only corn ears and a few upper stalk leaves ever enter the threshing unit. Design of headers and platforms are critical for maintaining an acceptably low level of harvesting losses. In situations where crops are badly lodged, the header must gently pick up the crop while avoiding further losses. The reel which aids in feeding crop material to the cutterbar operates at a peripheral speed slightly faster than the ground speed. Reel height above the cutterbar and reel speed are adjustable from the combine cab. Down crops require the header to operate on the soil surface, but ideally to not pick up any loose soil or soil clods which might result in added foreign material (FM) to the grain.

The feeding unit usually consists of a variable speed chain-type conveyor that carries cut crop material or corn ears from the header to the threshing mechanism. The feeding unit must also provide a uniform distribution of crop material to the threshing unit and introduce the material at the proper angle to the threshing unit.

Threshing is performed by either a conventional cylinder or rotary threshing unit. The rasp bar is the most common type of cylinder/rotor used in corn and soybean combines. Typically, about eight rasp bars are mounted on the periphery of a rotating cylinder to thresh crop material against stationary concave bars. In conventional cylinder combines, the cylinder is mounted perpendicular to the flow of crop material, Figure 3. Open grates between the concave bars allow threshed kernels to quickly escape while material other than grain (MOG) is propelled rearward. Huynh et al. (1977) provided an analysis of the threshing process. Basically, kernel threshing occurs due to impact forces exceeding kernel-to-cob or kernel-to-pod attachment strength. With rotary threshing, rotors are placed parallel to the flow of crop material, Figures 1, 2, and 4. Several small impacts are used to thresh the grain. Threshed grain is centrifugally propelled through the concave and separated from crop material, Depauw (1977); Floyd and Ewing (1977). Spacing between the cylinder/rotor and the concave is adjustable and is an operator controlled adjustment that should be made as crop conditions change. The operator can also vary cylinder/rotor speed.

The separating unit removes loose corn kernels from cobs and other plant materials or loose soybeans from pods and stems. In a conventional cylinder combine, separation is performed by accelerating the crop material rearward with a shaking motion created by straw walkers. Loose grain can fall through openings in the straw walkers and is caught by augers or oscillating conveyors that carry loose grain to the cleaning unit. In a rotary combine, straw walkers are eliminated since the latter portion of the rotor provides centrifugal separation of grain from crop material.

The cleaning unit or shoe consists of two sets of sieves and a variable speed fan. The top set of sieves is known as the chaffer while the bottom is called the cleaning sieve. Both have variable openings such that loose grain can easily drop through the chaffer to the cleaning sieve. Density differences between plant materials and the grain kernels allow chaff, stems, and pods to be suspended and forced rearward by air from the fan, while size differences allow threshed kernels to fall through the front portion of the chaffer. Srivastava et al. (1986) found that as kernel density increases, the separator capacity also increases. If properly adjusted, the rear section of the chaffer will allow any unthreshed kernels to fall through and be carried by the tailings conveyor back to the cylinder or rotor for re-threshing. The operator can safely observe excessive re-cycling of unthreshed grain on some combines. A large amount of return conveyor tailings provides a warning that cylinder/rotor speed may be excessive, concave clearance may be too close, or sieve settings need to be closed.

In the cleaning unit, an increase in fan speed provides greater removal of light crop material at the risk of losing some extra grain. Fan speed should be matched to the total amount of grain and MOG to be cleaned. Particles of dirt, weed seeds and other materials that are smaller than kernels can optionally be removed using a perforated section in the clean grain auger or in the clean grain elevator.

The grain transfer unit consists of two parts: 1) a clean grain auger feeding a paddle-type elevator that carries clean threshed grain from the bottom of the cleaning sieve up to the combine grain tank where it is often distributed with another auger; and 2) small auger(s) at the bottom of the grain tank that feed(s) the unloading auger which is used to quickly empty the combine grain tank. Since the largest combine tanks contain up to 310 bu, a large diameter auger is required to permit unloading in an acceptably short period of time of less than 3 minutes.

Performance Parameters

Performance parameters of combines refer to how crop conditions and combine components interact to achieve a balance between a timely harvest, with acceptably low harvesting losses, and acceptable grain quality. (The grain quality factors will be discussed in more detail in the subsequent section.) To be competitive, a combine manufacturer must achieve an optimal balance between harvest capacity, harvest losses, grain quality, and operator safety and comfort, and cost. Combine fuel efficiency is also a concern but not the primary factor when designing combines. Conditions such as crop maturity, moisture content, standability, insect or disease presence and amount of weeds present all affect combine performance.

Maturity and Moisture Content

Physiological maturity occurs when grain has reached its maximum dry weight. For corn this is usually at about 30 to 35 % moisture, Aldrich (1970). Generally, maturity occurs when the black hilar layer forms just beneath the tip cap of a corn kernel. Kernels at the tip end of a corn ear are usually drier than those at the butt end. As much as 6.9 percentage points of moisture difference were found from one end of an ear to the other end, Weller (1985). Typical fall dry down rates for standing corn are about 0.3 to 0.7 percentage points per day, Shove and Bateman (1968); but to extend the harvest season, farmers typically plant early, middle, and full season hybrids. While corn can be physically harvested at 30 to 35 % moisture it is so damaging to the soft pericarp of the kernel that it is not recommended. The exception to this rule occurs in Northern states during wet fall harvest periods and in many European countries, where the crop may not get harvested otherwise. In the Midwest, it is generally recommended to not harvest until 26 % moisture if possible, Siemens (1987). For highest possible quality, a major snack food producer requires that corn not be harvested until reaching 20 % moisture content. At this moisture the pericarp is sufficiently strong to withstand threshing with minimal damage.

For soybeans, physiological maturity occurs when maximum dry weight occurs. As soybeans dry down for the first time, it is generally recommended to not harvest until reaching 13.5 %. Harvesting can be accomplished at higher moistures but 13.5 % provides a little more time for green beans in upper pods to mature. Standing soybeans are very hygroscopic and will readily absorb moisture overnight or during high humidity periods. After once field dried to 13.5 %, soybeans may be harvested at moistures of 15 %. Brizgis et al. (1980) found that soybeans at 14.4 % moisture in the morning could easily dry to 11.4 % by afternoon, 7 hours later. While soybeans are usually marketed at 13 % moisture content, they can easily dry to 10 % or less by evening in the field. Soybeans below 12 % moisture are exceptionally susceptible to shatter loss during harvesting. Thus, after the first dry down, it is desirable to harvest at moistures between 15 and 13 %.

Harvesting Losses

Harvesting losses fall into categories of preharvest losses, header losses, threshing, and separation losses. Preharvest losses represent kernels, ears, or pods that are on the ground prior to combining. Such losses are not attributable to the combine. Gathering unit or header losses are due to failure of the header to collect and deliver all standing and lodged grain to the threshing mechanism. Cylinder or threshing losses represent those kernels still attached to corn cobs or beans still attached to pods after threshing. Separating losses are due to failure of removing loose grain from crop material causing grain to be lost from the rear of the combine.

For soybeans with a 40 bu/A yield, acceptable loss levels are shown in Table 7. Total losses are measured by placing a frame having a 10 square foot area over the entire cut swath and counting soybeans inside the 10 square foot area. A value of 4 soybeans/square foot represents a loss of approximately 1 bu/A.

An extensive study of soybean harvesting losses was conducted by Lamp et al. (1962) covering the years of 1956 to 1960. During this time period, total soybean field losses varied from 10 to 19 %. Of these losses, 80 % were gathering losses caused by the combine header. Gathering unit losses can be further subdivided into: a) shatter, 55 %; b) loose and lodged stalks, 28 %; and c) stubble losses, 17 %, Nave and Wax (1971).

Of the three losses from the gathering unit, shatter losses are the largest and are caused by the header shaking the plant during cutting. The pods pop open and the beans drop out onto the ground. From a survey of 35 combines operating in Illinois, Arkansas, and Mississippi, total soybean header losses ranged from 2.2 to 11.1 %, Nave et al. (1973). Following that time efforts have been made by researchers and combine engineers to reduce header losses. Improvements include cutterbars with lipless guards and sickle and guard spacings less than 3 inches apart to reduce shatter loss. Other modifications include floating cutterbars, floating flexible cutter bars, and soybean row-crop headers, Nave et al. (1979). The floating and flexible cutterbars have height sensors that mechanically or electronically control cutterbar height to maintain stubble heights less than 2 inches above the ground. Nave (1979) reported average losses with a floating flexible cutterbar header to be 30 % less than floating rigid cutterbars. The average losses over a two year period were 5.5 % for the floating flexible cutterbar header compared to 10 % for a rigid cutterbar. A row-crop header using a rotary-knife cutting mechanism reduced loss levels to 4 % of yield, Nave et al. (1977). They also found total platform header losses for certain varieties to be about 30 % lower in narrow 7-inch rows instead of 30-inch rows. Currently header losses below 3 % of yield is considered good.

Stubble losses occur when pods are set very low on the soybean stalk which is common for some varieties. To reduce stubble losses, the cutter bar must cut below the lowest pod. This practice inadvertently introduces some soil into the combine. Most soil is aspirated from the rear of the combine unless there are some soil particles about the same size as the kernels that pass through the cleaning sieves with the soybean kernels.

Weeds can also be a culprit for not achieving maximum production yield and quality. Nave and Wax (1971) found that one smooth pigweed per foot of row in 30-inch row width soybeans, reduced yield by 25 %. One giant foxtail per foot of row in 30-inch row width soybeans, reduced yield by 13 %. Furthermore, harvesting before frost (weeds were not desiccated) resulted in combine threshing and separating losses of 1.3 to 1.4 % at ground speeds of 3 mph, compared to 0.3 % loss for weed-free beans at the same speed of harvesting. By drastically reducing harvest speed to 1 mph, threshing and separating losses were reduced in the weedy beans. However, it was found that there were 50 % more bean pods on the lower 6 inches of the plant in weedy plots than in the weed-free plots. Thus, the combine has to cut extra low in weedy beans, taking in all the weeds, just to harvest the beans. Their study did not report on how much extra weed seed was found in the grain tank. They reported that after weed desiccation due to frost, the combine could operate faster, while keeping threshing and separating losses low.

Harvesting losses for corn are itemized in Table 8. Pre-harvest losses are extremely variable. They are affected by weather conditions, insect infestation, crop year, and variety. Pre-harvest losses due to stalk lodging are a usual penalty for late harvesting. Nolte et al. (1976) reported that ear loss in bu/A averages about one-third of the percentage of stalks that are lodged. In Ohio, stalk lodging increases by about 5 % for each week corn harvest is delayed past October 15. Acceptable losses from combining range from 0.6 to 2.5 bu/A, Byg (1974). Losses can be measured by placing a 10 square foot frame over the entire number of rows harvested in one pass. Then a count of 2 kernels/square foot represents a loss of 1 bu/A.

Ayres et al. (1972) reported that total machine loss for 84 combines checked in Iowa in 1971, ranged from 3.1 to 5.6 bu/A and averaged 3.7 bu/A. By including preharvest losses, the total losses were 4.7 to 8 bu/A.

Timeliness of harvest

Timeliness of harvest often takes precedence over other factors such as optimal moisture content needed for reduced damage or reduced field losses. For any geographical region of the United States, there are a limited number of days in which field conditions will permit harvesting. For example, in Central Illinois, September and October each have 16 harvesting days, for 8 years out of 10 based on statistical weather records, Successful Farming (1979) and Nolte et al. (1976). To calculate combine effective field capacity, the following formula can be used:

$$EFC = S\ W\ E\ /8.25$$

where: EFC = effective field capacity, A/hr.

S = speed of travel, miles/hr.

W = width of header, ft.

E = field efficiency, % (Assume 70 to 80 %)

To reduce combine investment costs, on a per bushel harvested basis, a producer should match combine size and number of combines to the number of usable harvesting days that is needed to harvest his total acreage. Thus, if excess combine capacity is not available, and due to the uncertainty of the weather, the producer is nearly always in the position of harvesting long hours without being able to delay harvesting just because grain moisture is too wet or too dry. The result of this dilemma is that the producer must often push the moisture limits and accept higher levels of pericarp damage in corn by harvesting too wet and higher levels of shatter losses in soybeans by harvesting too dry. In spite of weather uncertainties and the busyness of the harvest period, the operator cannot afford **not** to take time to make periodic combine adjustments as crop conditions vary. Byg (1974) reported that when harvesting $6/bu soybeans, operators that take the time necessary to adjust the combine and check for losses could reduce losses from 10 % to 3 %, saving $50.40/hour of combine operation time.

In many parts of the cash grain corn belt, farmers also want to do fall tillage on harvested corn acres so that earlier planting can be done in the spring. Nolte et al. (1976) found that a one-week delay in planting corn provided a yield reduction of 4 %. This practice places further demands on a high speed harvest. Therefore, even if a farmer purchases a combine with more capacity than needed, the farmer is still likely to harvest as quickly as possible so that fall tillage operations can be performed.

In spite of all the demands placed on a combine for high capacity harvesting with minimal loss, field harvesting is only one part of the total harvest operation. Trucks, wagons, and drivers must be available to provide timely combine tank unloading. To be able to remove wet grain from the field it is essential to have drying and/or wet holding storage capacity capable of keeping up with the combine. If grain must be hauled to an elevator, long truck lines will also slow harvest. Thus, it is essential to match hauling, drying, and storage capacity with harvesting capacity.

Combine Adjustments and Operator Considerations

Combine adjustment descriptions in operator's manuals and most extension publications are notoriously brief and vague when it comes to combine adjustments such as cylinder/rotor speed, concave clearance, cleaning fan speed, and chaffer and sieve openings.[2] With all the knowledge today's farmer needs to keep his day-to-day operation going, and his likely worry of keeping the combine from breaking down or repaired when it does break down, a farmer does not have much time left for thoroughly understanding and correctly setting his combine. Custom combine operators would have an advantage of longer seasons of operating experience over the farmer that may be operating in several crops even in the same day, Ayres et al. (1972).

Basically, the cylinder/rotor speed is adjustable from the cab and required peripheral cylinder/rotor speed varies by type of crop, crop varieties, and by moisture content of the crop material. Generally, as crop moisture decreases, threshing speed should also be decreased.

The concave setting (distance between the peripheral edge of a cylinder or rotor and the concave) has one optimal setting.

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[2] An exception to this statement is a new brochure entitled, "How to improve grain quality without cracking up" by Deere and Co. It provides a guide to combine adjustments for food corn published in response to a major snack food processor that pays premiums to farmers for low damage in corn.

Basically, the closest distance at the back of the concave must always be slightly greater than the diameter of the soybean kernel or of the average corn cob to be threshed. Concave settings too close cause severe kernel grinding-like damage. If the concave setting is too wide, corn kernels will be left on cobs and soybeans will be left in pods which contribute to high threshing losses.

Excessive cylinder/rotor speed can create symptoms similar to concave settings that are too close. With excessive cylinder/rotor speed, kernels are damaged, cobs break up into small pieces causing straw walkers to plug or more difficult separation which leads to heavy amounts of material in the return elevator. With cylinder/rotor speed too slow, threshing is also not complete.

Because of the ease by which a non-optimum cylinder/rotor speed setting can be confused with an incorrect concave setting, considerable operator experience is required when the goal is to maintain low grain damage and low threshing and separating losses. Anyone can drive a combine, but not everyone who drives it can operate it at its highest capabilities. To achieve lower loss levels and higher quality, operators need to be fully trained. On newer combines, manufacturers have added grain loss monitors and numerous shaft speed indicators to better assist the operator. These will be detailed in the technology section.

GRAIN QUALITY FACTORS AFFECTED BY HARVESTING

The primary quality factors in corn and soybeans that are affected by combine harvesting are the percentages of damage to the pericarp or seedcoat, internal cracks, amount of broken corn or splits, the amount of foreign material (FM), and germination percentages. Pericarp damage, internal cracks, broken kernels, splits, and loss of germination are attributable to threshing and handling components; while FM can be attributed to header height, separating, and cleaning components of the combine. Basically, when corn or soybeans are harvested at high moisture contents, the pericarp, hull, or seedcoat is soft and pliable. While the moist kernel deforms easily when a force or impact is applied, a greater impact energy is needed to thresh wet kernels than dry ones. Thus, wet kernels suffer more pericarp damage than dryer kernels.

Corn

Pericarp Damage

Pericarp damage is not directly measured in the U.S. Grading Standards, USDA (1980). Yet, excessive pericarp destruction eliminates the effectiveness of the pericarp for providing a protective covering for reducing the chance of fungal and insect invasion. If pericarp damage is severe enough, pieces of pericarp are broken which eventually add to the BCFM which is measured in the grading standards; however, a kernel missing a piece of pericarp is not included in the broken or damaged kernel categories of the standards. There is also a tendency for high pericarp damage to cause test weights to be lower, Hall and Hill (1974). Hall (1972) found combine-shelled corn to have about 1 lb/bu lower test weight than hand-shelled corn of the same variety. (A probable explanation is that kernels with pericarp damage have more bulk and more friction between kernels, preventing them from packing as tightly into the quart test weight kettle.)

One of the methods used to characterize pericarp damage is the fast green dye test. For this test a representative sample is sieved over a 12/64 in. round-hole sieve, then immersed in a 0.1 % solution of fast green dye (Fisher Certified Reagent) and distilled water for 10 minutes, Paulsen and Nave (1980), Chowdhury and Buchele (1978). The sample is removed and rinsed with tap water and allowed to dry on paper towels. Next, the sample is separated into categories of: severe, minor, and no damage. Severe damage includes broken pieces and kernels with large pericarp cracks, or missing pieces of endosperm. Minor damage includes kernels with any pericarp cracks that absorbed the dye. No damage includes only those kernels with no dye absorbed or only a slight amount at the kernel tip cap.

In evaluating harvest damage, Paulsen and Nave (1980) found that corn harvested with two rotary and one conventional cylinder combine at 29 % moisture content had levels of severe fast green dye damage ranging from 11 to 12 %. The same three combines operating in the same field at 18.6 % moisture had severe damage levels of 4.3 to 6.5 %. Thus, severe pericarp damage was reduced by about 50 % by harvesting at a lower moisture content.

Kline (1972) sampled shelled corn from combines and farm trucks and wagons delivering new harvested corn to country elevators in 1969 and 1970. He analyzed 500 samples for BCFM, mechanical or pericarp damage, breakage susceptibility, and germination percentages. Average BCFM was 0.6 % and only 2 of 500 samples exceeded 3 %. Mechanical damage was classified as visible and hidden damage. Visible damage included BCFM passing through a 12/64 in. sieve and those chipped or crushed kernels above the sieve. Hidden damage included whole kernels with a portion of the pericarp missing or having a hairline crack. They found the samples averaged 5.5 % visible damage, and 40.5 % hidden damage. Breakage susceptibility tests at a uniform moisture averaged 4.5 %.

Ayres et al. (1972) conducted a field survey of 80 combines operating in fields in Iowa in 1971. They found BCFM ranged from 0.5 to 1.1 % as harvest moistures increased from 13 % to 23 %. They found visual damage to range from 3.8 to 6.5 % with the higher amounts of visual damage occuring at the higher harvest moisture. They found hidden damage ranged from 25 to 39 %.

The effect of moisture content on cylinder/threshing damage was investigated by Waelti and Buchele (1969). They found kernel strength (determined by quasi-static loading of individual kernels between parallel plates up to kernel bio-yield point) decreased by a factor of 50 % as moisture increased from 15 to 40 %. They also threshed kernels and inspected for visual damage (breaks, cracks, and seedcoat injuries). With their classification, they found 15 % damage at 15 % moisture content. At 30 % moisture, damage was 30 %. A log-log plot of the relationship followed a straight line and kernel damage in % was found to equal 0.882*(Moisture, %)$^{1.039}$. Thus, seedcoat or pericarp injury became much greater as harvest moistures increased.

Chowdhury and Buchele (1976) investigated various types of pericarp damage due to laboratory cylinder threshing. They reported that detached kernels bounced between the cylinder and concave bars several times before the kernels could fall through the concave grate. Cylinder speeds of 440, 540, and 640 rpm were used with moisture contents of 27, 22, 19, and 16 %. Total damage (pericarp plus BCFM) increased from 26 to 41 % as cylinder speed increased from 2591 (440) to 3774 fpm (640 rpm). BCFM went from about 0.5 to 1.0 % as cylinder speed increased. Averaged over all cylinder speeds, total damage was lower at the 22 % moisture than at the 16 or 27 % moistures.

Mailander et al. (1983) inspected corn samples harvested with a single rotor combine at moisture contents of 18.1, 22.7, and 29 %. Visual damage increased exponentially from 5 % to about 30 % as rotor speed increased from 350 rpm (2200 fpm) to 700 rpm (4400 fpm) for the 18.1 % corn. At 22.7 % harvest moisture, visual damage ranged from 6 to 16 % as rotor speed increased. At 29 % moisture, visual damage stayed nearly constant at about 16 % for all rotor speeds. Thus, increases in rotor speed increase damage on low moisture corn more than on high moisture corn.

Anazodo et al. (1981) investigated concave separation efficiency, shelling efficiency, and kernel damage for a rasp-bar cylinder for corn at three different harvest dates. They found that as corn cob crushing strength increased, combine separation and shelling efficiency increased also. They also determined that corn harvested at 31 % moisture had 54 % kernel damage (using a colorimetric fast green dye method); while corn harvested at 23 % had 30 % kernel damage.

Moreira et al. (1981) used a laboratory test device to impact individual corn kernels at velocities of 1968 (10), 2755 (14), and 3542 fpm (18 m/s) at moistures of 29, 20, and 13 %. Kernels impacted on the side or corner developed more internal stress cracks than kernels impacted on their top crown surface. At speeds typically found during threshing of 2755 fpm, about 15, 47, and 80 % internal cracks were found in the side-impacted kernels at moistures of 29, 20, and 13.4 %, respectively. At the higher impact velocity of 3542 fpm, about 50, 81, and 93 % internal stress cracks were found for each of the three moisture contents, respectively. Thus, corn kernels increase in internal cracks as moisture decreases and as impact velocity increases. Evidently, some kernels had both internal and external damage. At 3542 fpm, side impact created 9, 26, and 67 % external damage for corn at moistures of 29, 20, and 13.4 %, respectively. This finding suggests more external damage is created at lower moistures, which is contrary to results of most harvesting studies. However, these impact tests do not include the cushioning effect of the wet corn cob nor do they assume cylinder/rotor peripheral threshing speed would be reduced as moisture decreases. These two factors probably account for the reason that general harvesting experience has been that wet corn sustains high amounts of pericarp injury due to the high impact energy needed to thresh wet kernels off of the wet cob. Moreira et al. (1981) did find that higher levels of breakage susceptibility as measured with a Stein breakage tester occurred at 13.4 % moisture than at 29 % moisture. Also they found breakage susceptibility increased as impact velocity increased for all moisture levels. Thus, the same conditions that created high internal cracks also resulted in high breakage susceptibility.

BCFM and Other Factors

The second major corn quality factor affected by harvesting is BCFM. BCFM is measured as the weight percentage of material passing through a 12/64 in. round-hole sieve plus any coarse non-corn material remaining on top of the sieve. The allowable limit for U.S. No. 2 Yellow Corn is 3 %. The effects of rotary threshing devices on BCFM were investigated by Paulsen and Nave (1980). They found that BCFM in clean grain auger samples for conventional cylinder, single rotor, and double rotor machines was consistently below 1 % at all cylinder/rotor threshing speeds. For corn harvested below 21 % moisture, BCFM was consistently below 0.5 %. However, BCFM levels in the grain tank were 0 to 0.1 percentage point higher than that at the clean grain auger. This increase in BCFM was more noticeable for the rotary combines than the conventional cylinder combine tested. Tank auger samples were significantly lower in cold-test germination than the clean grain auger samples. Cold-test germinations were reduced due to extra handling to reach the grain bin. Since most seedcorn is picked and dried on the ear, germination reductions due to combine harvesting has not been a major concern. For all of these tests, separating and threshing losses were below 0.6 bu/A. All of the machines were adjusted and set by company representatives, so the study provides an indication of the BCFM levels that these combines were capable of obtaining. Stein breakage tests ranged between 0.9 and 4.5 %. No differences in Stein breakage percentages were found among combine types.

In a later harvesting study by Racop et al. (1984), the amounts of fine material for two conventional cylinder combines and a cylinder-system combine at harvest moistures of 26, 24, and 16 %, were also consistently below 1 %. Cylinder and separating losses were less than 1.5 % at MOG feed rates of 594 lb/min. One of the conventional cylinder combines had fines percentages below 0.57 for all three moisture levels. Fines were determined by mechanically sieving over a 12/64 in. sieve. They found susceptibility to future breakage as measured by a Stein breakage tester, was in the 8 to 11 % range for corn harvested at 26 % moisture, whereas at 16 % moisture, breakage susceptibility was cut in half.

Byg and Hall (1968) checked samples from 126 farmer operated combines over a three-year period. They found BCFM ranging from

0.2 to 7.3 %. Average BCFM for the years 1964, 1965, and 1966 was 1.5, 1.3, and 2.3 %, respectively.

Hall and Johnson (1970) determined corn breakage through a 12/64 in. sieve for corn shelled in a laboratory rasp-bar threshing cylinder at corn moisture contents of 15 to 38 %. They found minimum breakage occurred at moistures between 20 and 24 %. However, the minimum was sharply apparent for a 600 rpm cylinder speed but less apparent at 400 rpm. This finding indicates that the effect of having **excessive** peripheral threshing speed at moistures below 20 % will likely cause much more breakage than it would at moistures above 24 %, Figure 5.

The effect of temperature on grain breakage during harvesting has not been well documented. However, based on handling studies at different temperatures, it could be expected that harvesting grain during cold weather would likely increase breakage. For example, Foster and Holman (1973) reported that a 40 F reduction in temperature resulted in a nearly 50 % increase in corn breakage in bucket elevator and grain thrower tests.

In general, pericarp damage can be reduced by harvesting at moistures below 26 %. Stein breakage susceptibility increases with increased pericarp external damage and internal stress cracks. Breakage is reduced as moistures decrease to about 24 to 20 %, and combines are capable of obtaining BCFM of 1 % or less.

Soybeans

The primary quality factors in soybeans which are affected by combine harvesting are the percentages of FM, splits, seedcoat damage, and germination. Lamp et al. (1961) found that in high-moisture soybeans at 17.1 %, crackage (splits, cracked kernels, and seedcoat cracks) increased and germination decreased as peripheral cylinder speed increased, Figure 6.

SaijPaul et al. (1977) investigated soybean quality obtained from a double rotor combine and a conventional cylinder combine from the same manufacturer. For Amsoy soybeans harvested in 1976 at 13.4 % moisture content, seedcoat crack damage was 5.8 % for the conventional cylinder and 3.9 % for the double rotor combine. FM levels were at about 2 % for both combines. Percentages of splits were 2.6 % for the conventional cylinder and 1.9 % for the double rotor combine. Splits were significantly lower for the double rotor combine than the conventional cylinder combine at the 18.2 and 9.3 % moisture levels also. At 13.4 % moisture, loss levels were very low (about 0.13 bu/A) and were not significantly different for the two machines. At the 9.3 and 18.2 % moistures, losses were much greater and the double rotor combine had significantly lower losses than the conventional cylinder machine.

Newbery et al. (1980) investigated Amsoy 71 soybean quality factors obtained from single rotor, double rotor, and conventional cylinder combines at harvest moistures of 13.3, 12.5, and 11.6 %. Four cylinder/rotor speeds were used which provided peripheral speeds ranging from 2361 (12) to 4133 fpm (21 m/s). Percentages of splits increased as threshing speed increased for all three combine types, Figure 7. However, the rate of increase was much lower for the rotary combine types. The optimal peripheral speed setting was in the 2755 to 2952 fpm range. In that range, splits were 4, 1.4, and 0.9 % for the conventional, single rotor, and double rotor combines, respectively. These levels of splits were obtained at the clean grain auger. Due to the additional handling with augers and paddle conveyers, the level of splits at the grain tank was 4.7, 1.9, and 2.3 % for the conventional cylinder, single rotor, and double rotor combines, respectively. One of the conclusions of the study was that handling added an additional 0.6 to 1.4 percentage points of splits to the sample.

In the Newbery et al. (1980) study, percentages of soybeans with seedcoat cracks ranged from 41 to 58 % and averaged about 50 % for all moisture levels and combine types. Stein breakage tests ranged from 13 to 40 %. Neither of the tests were significantly affected by threshing mechanism type or by cylinder/rotor threshing speed. Levels of FM ranged from 0.1 to 1.3 % with an average of 0.4 %. Composite threshing and separating losses at the 2755 to 2952 fpm peripheral threshing speed were 0.14, 0.21, and 0.14 bu/A for the conventional cylinder, single rotor, and double rotor combines, respectively.

Mailander et al. (1983) harvested soybeans with a single rotor combine and re-confirmed that visual damage (determined on 200-kernel samples) increased as rotor speed increased and that damage decreased as moisture content decreased. At a typical field operating rotor speed of less than 600 rpm, visual damage averaged about 10 %. Splits and FM were not measured.

In general, soybean splits increase with increasing peripheral threshing speed, but the increase is greater for the conventional cylinder combine than the rotary combines. The overall percentages of splits were also higher for the conventional cylinder machine than the rotary combines. However, at normal threshing speeds all of the combines could achieve less than 4 % splits. FM levels below 0.5 % are possible but are dependent on weedy conditions and how low the header must operate.

In the Southeastern U.S. states soybean harvesting is complicated by a warm wet climate that is highly conducive to weed growth. Frans (1980) reported that most of the soybean varieties grown in the South are the determinate bushy type, which tend to shade the soil fairly early in the growing season. Wide ranges of annual broadleaf and grass weeds were found in soybean fields prior to the use of herbicides. Ecological weed shifts have occurred with the use of herbicides, leaving several annual broadleaves and perennial vines very difficult to control with cultural or chemical means. He also stated that Common Cocklebur is an annual broadleaf that became difficult to control after increased use of preemergence herbicides and that Johnsongrass is particularly troublesome for soybean fields in the South. Oliver et al. (1976) reported that Tall Morningglory is becoming a dominant weed in the Mississippi Delta region, which adds to the difficulty of combine harvesting and increased damage to soybeans. McWhorter (1987) stated that Common Cocklebur, Johnsongrass, Hemp Sesbania, Morningglory, and Pigweed were particularly troublesome weeds contributing to harvesting problems in the South.

McWhorter and Anderson (1979) found that Hemp Sesbania populations above 4,330 plants/A increased levels of damaged kernels and moisture content of harvested soybeans. In addition to reducing soybean yields from 10 % (with 3280 weeds/A) to 80 % (with 52,270 weeds/A), Hemp Sesbania seeds are difficult to clean from soybeans. With 650 plants/A of Hemp Sesbania, they found 0.8 % F.M., 12.7 % moisture, and 1.2 % damaged kernels in combine samples with a yield of 29.9 bu/A. At 4,330 plants/A of Hemp Sesbania, they found 6.7 % F.M., 14.0 % moisture, and 2.2 % damaged kernels with a yield of 23.9 bu/A. At 52,270 weeds/A they found 20.3 % F.M., 16.8 % moisture, and 5.1 % damaged kernels with a yield of 6.0 bu/A.

McWhorter and Anderson (1976) reported that Common Cocklebur is one of the most serious weeds in the Southeastern U.S. and may decrease soybean yields by 50 to 80 %. They reported that farmers usually increase cylinder speed to force weed debris through the combine. The excessive cylinder speed leads to mechanically damaged beans, splits, and seedcoat cracks. With excellent weed control they obtained 31 bu/A yields at 12.4 % moisture, 3.0 % splits, 1.2 % damaged kernels, and 0.7 % F.M. With no weed control they obtained 16.6 bu/A at 14.4 % moisture, 4.8 % splits, 2.2 % damaged kernels, and 6.0 % F.M.

The weed studies did not state what type of conventional cylinder combine was used. They did indicate that severe F.M. and damaged kernel combining problems occur when adequate weed control can not be maintained. The problem is further increased by a low likelihood for frost in the South during harvest to help dessicate the weeds. Thus, the tendency is to operate the cylinder/rotor at excessive speeds to thresh all of the extra MOG, ultimately causing increased kernel damage and splits. The extra MOG also overloads the separating and cleaning components. Presummably a good operator would avoid the temptation to increase cylinder/rotor speed, but would instead reduce ground speed in weedy conditions. Because of huge yield losses (10 to 80 %) due to weed competition for moisture, soil nutrients, and sunlight, the most economically sound solution to high F.M. and mechanical damage would be to reduce the number of weeds by cultural or chemical means.

EMERGING TECHNOLOGIES

Basically, changes in harvesting technology have been evolutionary rather than revolutionary. For example, the rotary combine was publicized widely in the popular farm press as a major breakthrough in harvesting, yet investigations on the idea of centrifugal separation had been reported some 15 years earlier by Lamp et al. (1960). With declining combine sales over the past eight years, it is even less likely that revolutionary changes in the self-propelled combine harvesting technology will occur in the next few years.

With present harvesting technology, combines are capable of achieving corn breakage levels below 0.5 % BCFM and soybean splits below 5 % at acceptably low loss levels. The problem remains in getting the operator to run the combine at the lowest damage level that the combine is capable of delivering. In recent years, rotary combines have received numerous farmer testimonials of improvements in grain quality. It is likely that the basis for these comments is that rotary combines tend to have a much more gradual increase in splits as rotor speed increases than conventional cylinder combines, Figure 7. In viewing the change in splits versus peripheral threshing speed, the rotary combines have a much flatter curve, indicating that if threshing speed was too high on a rotary combine, splits would not be increased as much as they would be on a conventional cylinder combine. Thus, threshing speed adjustments tend to be more forgiving on a rotary combine than on a conventional cylinder combine. From a grain quality perspective, emerging technology needs to be aimed at helping the farmer to better adjust his combine to fully obtain the maximum quality levels already possible.

Automation and Controls

Emerging technology appears to be of an evolutionary nature aimed at providing more information to assist the combine operator.

With new class 6 combines with headers approaching list prices of $160,000, electronic sensors and displays are a relatively insignificant part of the overall cost.

Grain Loss Monitors

One of the recent aids for improving harvesting has been the introduction of the grain loss monitors. Loss monitors are mounted behind the separation and cleaning sections of the combine. They electronically sense the number of kernels that impact on a small acoustical pad. Kernels are electronically detected by their characteristic voltage waveform created upon impact with the acoustical pad, Gullacher and Smith (1979). They do need to be calibrated to actual losses measured in the field. Interestingly, grain loss monitors are marketed as a means to reduce threshing and separating losses; however, they can also be an effective aid for assisting an operator to reduce threshing speed until losses become noticeable, thus reducing grain damage. Figure 6. shows that typically, cylinder losses decrease as threshing speed increases to about 4000 fpm, then the curve remains nearly flat. Crackage continually increases as threshing speed increases. Thus, as grain dries in the field, reductions in cylinder/rotor speed should be made to reduce breakage until threshing losses, observable on the grain loss monitor, start to increase.

Information Sensors

Information sensors related to the harvesting function in addition to grain loss monitors which are commonly provided as original equipment on newer combines include: digital readout of cylinder/rotor speed, cleaning fan speed, feeder shaft speed, reel speed, engine speed, and ground speed. Several manufacturers now have warning lights for speed reductions of: the cleaning fan, cylinder/rotor, discharge beater, straw chopper, feeder, rear beater, clean grain elevator, and return elevator. There are warning lights for a full grain bin, an open stone trap, and unloading auger position. Presently, when this information is received, the operator can make changes from the cab, but he must decide if changes are needed. Unfortunately, most of the sensors do not provide "real performance information" but instead provide only information on whether a shaft is rotating or on the speed of rotation. The operator must then interpret (based on experience) how shaft speed affects real performance. More work is needed on the development of new biosensors that directly sense the desired performance.

Automatic Controls

With the advent of low-cost microcomputers and better sensors for real-time measurements, it is just a matter of time until many of the present operator decisions will become automatically controlled by computers. As early as 1977, Brizgis et al. (1980) reported on a capacitive type moisture sensor used in an electronic circuit to reduce cylinder threshing speed as soybean kernel moistures decreased. Baskin et al. (1981) used a Finnish moisture measuring instrument, OT-Teydas Industries, to measure moisture with temperature compensation for continuously flowing soybeans on a combine. Mailander et al. (1982) investigated four continuous-flow moisture sensors but found that the density of grain in the region of the sensor needed to be controlled. Reliable and direct sensing of grain and crop material properties is obviously an important parameter needed before automatic control can be achieved.

Accurate measurements of material flowrates to the threshing unit are also needed. Belgian researchers, De Baerdemaeker et al. (1985) developed an impulse-type grain flow meter for use on a combine. Schueller et al. (1985) measured torque on the feeder conveyor shaft to approximate the feedrate on material entering the threshing mechanism.

One of the first attempts at developing a totally automatic controller to improve harvest efficiencies and reduce soybean damage was described by Miles et al. (1979). Their objectives were to automatically adjust forward speed, rotor speed, fan speed, reel speed, and concave opening to minimize losses and damage to soybeans. Inputs to their controller included soybean moisture, biomass moisture and quantity, grain loss, and present ground, reel, rotor, and fan speeds, and concave position.

A Canadian researcher, Famili (1983), built a microprocessor based automatic feedrate controller. Its function was to vary ground speed in order to control material throughput for corn and soybeans. LeFlufy and Stone (1983) also developed a microprocessor control system to control combine forward speed based on crop feedrate. Kruse et al. (1982) developed a ground speed controller that had inputs from engine rpm, a pressure signal from a hydraulic drive motor to the feeder conveyor, and a ground speed set by the operator. The controller was able to successfully vary ground speed to maintain a full load on the threshing mechanism without plugging.

Schueller (1985) reported that most automation equipment on combines was electro-hydraulic and some of the current applications of automation were automated leveling on hillside combines, automatic header height control, automated reel speed to increase as ground speed increases, and engine shutdown due to low liquid or pressure levels. Schueller (1985) reported that considerable research effort in the combine automatic controls area had also been performed at institutions outside of the U.S., such as the Agricultural University, Wageningen, Netherlands (van Loo, 1977 and Huisman, 1983); at Hohenheim, West Germany (Eimer, 1974); and at Kyoto University in Japan (Kawamura et al., 1977).

Future Changes

In the immediate future the relatively low sales of combines dictates cost cutting measures from a production manufacturing standpoint and ways to obtain more productivity and efficiency from the same machine. In the longer term it is likely that combines will have computer-assisted controls for increasing throughput, reducing losses, and for improving grain quality. To assist in operator education, one combine manufacturer is marketing a PC computer driven "Flight Simulator" type of software that is designed to help in selecting proper combine adjustments, Mowitz (1987). Turner et al. (1985) reported that Deere Harvestor Works had developed a combine simulator that provides grain loss data behind the header and the separator and also provides sample damage information in response to cylinder speeds, concave settings, fan speed, chaffer settings, chaffer extension, and sieve settings. Schertz (1988) reported excellent results using the combine simulator algorithm with students. The simulator provided feedback on damage to grain, and more widespread use would certainly help combine operators adjust combines for lower losses and less damage to grain.

Another approach being developed to assist the combine operator is an expert system software program designed to run on a computer at a combine dealership, Schueller et al. (1986). The software is able to ask questions related to combine threshing and processing performance and using speech synthesis, it can tell the operator how to adjust the combine to improve its performance.

Perfection of continuous flow crop and grain moisture sensors will be necessary for reducing losses and improving quality. If incentives for improved quality existed, it would be possible to develop an on-combine continuous-flow sensor for detection of kernel damage using computer vision image processing on random samples of grain.

Ultimately, technology will be available to sense crop moisture and grain losses, and use computer vision to provide an analysis of the latest grain tank sample to indicate pericarp damage and broken kernels. These three inputs along with other biosensor information and the shaft speeds presently monitored would provide the basis for a totally automated combine.

ANALYSIS OF CURRENT HARVESTING TECHNOLOGY

As current harvesting technology is analyzed, it becomes apparent that technology varies depending on crop conditions and climate. For example, Ness (1978) reported that in South Africa, corn was generally harvested at moistures below 14 %. Row widths varied from 36 to 90 inches depending on soil fertility and water availability. About 54 % of the combines were pull type; however, as yields increased, (1974 average corn yields were about 36 bu/A) it was estimated that self-propelled combines would become more prevalent and cost effective. Ness (1978) also described the "Slattery" harvester which used an axial cylinder configuration. The cylinder had two threshing bars, followed by five helical flights that aided separation. This particular design worked well for low moisture conditions, but at corn moistures over 20 % performance was limited. Thus, due to low moisture harvesting conditions in South Africa, a simple low-capacity, low-cost combine was used. Ness (1978) did not indicate to what extent harvest damage was caused by this combine.

In Argentina, another major corn producing country, harvest moistures are generally in the 28 to 15 % moisture range, Hill and Paulsen (1987). They found combine samples from five farms averaged 0.3 to 1.3 % BCFM with an average of 0.7 %. The corn, which was a flint type, had 94 % whole kernels. Combines used were predominately conventional cylinder types with five-row 70-cm corn heads.

In Western Europe, Naessens (1978) reported that in their field tests in France, corn harvest moistures were seldom below 30 % and often around 40 %. He also pointed out that in Western Europe more emphasis is placed on small grains since 84 % of the cereal crops are small grains, whereas in North America the figure is about 60 %.

As current technology for providing pertinent quality of grain for various end uses is analyzed, it is apparent that all end-users would prefer low breakage, low FM, and low levels of pericarp or seedcoat damage. One can argue that, unlike other uses, broken corn and pericarp damage do not matter if the grain is used as livestock feed. This may be true only if grain is to be fed immediately. But obviously livestock must be fed year-around. Thus, most of the grain designated for livestock feed cannot be fed immediately and must be stored. To be stored, grain must be dried. To be dried it must readily allow air to pass through intersticial spaces between kernels. Any breakage, fines, or foreign material present reduces the airflow through grain, if not removed. Any pericarp or seedcoat damage leaves the kernels more vulnerable to undesirable fungal and insect activity, causing untold losses in grain dry matter out of stored grain that can never be weighed. Thus, there is no end use of grain that can produce an equally high quality product from damaged grain compared to non-damaged grain.

Breakage, fines, and pericarp or seedcoat damage, germination, and internal cracks in corn and soybeans are basically the only quality factors that are directly affected by combine harvesting. The weakness in our harvesting system from a grain quality perspective can be demonstrated by examining how the current marketing system reacts to these factors. For example, in corn, breakage and fines up to 3 % are allowed in U.S. No. 2 Yellow Corn (which is the usual grade marketed from the farm level) with no discount. Prior to 1987, no distinction was made between breakage (broken corn) and FM. This former practice has, in fact, encouraged farmers to deliver 3 % BCFM regardless of whether the combine was capable of achieving 0.5 % BCFM or less. In soybeans, splits of up to 10 % are allowed in U.S. Grade No. 1 Soybeans (which is the usual grade marketed from the farm level) with no discount. Combines can deliver less than 4 % splits, but if beans are hauled directly to market, there is no incentive to take the time to adjust a combine to deliver less than 10 % splits. In the case of FM, U.S. No. 1 soybeans are allowed 1 % FM. In some years with badly lodged soybeans with weedy conditions, it may be difficult to keep FM below 1 %; but under good conditions, combines can deliver FM below 0.5 %. Of the grading factors for soybeans, FM is more likely to fall outside of No. 1 grade than is the percentage of splits.

In the grading standards no mention of measuring pericarp damage in corn or seedcoat damage in soybeans is made, USDA (1980). If these types of damage fall under the category of "Otherwise Materially Damaged" they are not described in the Grading Standards Handbook. By measuring and including pericarp damage in either the damaged kernel category or in a separate category, it would be possible to provide an incentive for harvesting with lower levels of pericarp damage.

Standardized tests and procedures using fast green dye or other suitable dye methods would need to be developed if pericarp damage was to be measured in corn. Other dyes or procedures would be needed for soybean seedcoat cracks. By first measuring pericarp or seedcoat damage, inducements for reducing this damage could be initiated.

A major snack food processing company has had excellent success in offering farmers a premium to harvest at lower moistures (around 20 %) with considerable attention to combine adjustments. They also measure pericarp cracks and internal cracks. They have found this corn to be a superior quality product which is worth substantially more to their processing operation than is U.S. No. 1 or U.S. No. 2 Yellow Corn. This company's experiences have generally shown that any combine if operated properly can meet their stringent quality requirements.

While data would lead to the conclusion that nearly any combine can deliver acceptable quality corn and soybeans, the tendency is for actual farmer operated combines to have higher levels of damage than the combine is capable of delivering. The solution to this dilemma is two fold: 1) greater educational efforts would help the combine operator to better understand the interactions between cylinder/rotor speed, concave opening, fan speed, sieve openings, with grain quality and grain losses; and 2) more monitoring devices and possible automatic controls on combines could also help the operator to better adjust his combine. (As older combines are replaced with newer ones, more monitoring devices will be available.)

It has been shown that rotary combines produced fewer splits in soybeans than conventional cylinder combines, while in corn the same effect on breakage was not evident. Since the splits-versus-threshing speed curve tends to be flatter for the rotary than for the cylinder threshing mechanisms, an excessive rotor speed would cause fewer splits than a conventional cylinder combine. Thus, the rotary tends to have a wider tolerance range than the conventional cylinder combine.

It would be great to hope for a major technology change that would drop harvest damage levels to zero. It is difficult to predict what advanced technology might do. However, as long as a mechanical process is used to thresh corn from cobs or soybeans from pods, there is a certain minimum amount of mechanical energy that must be applied in a limited time interval. Generally, impact velocities in the range of 2755 fpm (14 m/s) are needed to remove kernels from the cob. Thus, from a mechanical threshing viewpoint, it would seem unlikely to see major changes improving threshed kernel quality in the near future. From an economic standpoint this conclusion is probably justified for two reasons: 1) an industry that has production capacity for 30,000 combines per year can not afford to make revolutionary changes when sales are down to 7700 units per year; and 2) there are negligible incentives for producing corn with less breakage or less pericarp damage or soybeans with fewer splits. This condition must change before combine manufacturers can be expected to invest in engineering and manufacturing costs of major design changes.

One of the easiest areas to make minor improvements in quality would be in the conveying and grain transfer systems. Augers cause considerably less damage when running full than when one-fourth full, Hall and Sands (1970). They also create fewer fines if running slower. Consideration for elimination of some augers, replacement of augers with belt conveyors, variable speed augers, and smooth transitions between augers and elevators could help reduce handling breakage and pericarp damage to grain from combines. Optimal threshing and separating settings would also reduce re-cycling of grain in the return conveyor.

SUMMARY

The number of combines sold in the U.S. has dropped from a yearly average of about 30,000 units during the 1970's to less than 7700 units in 1986. With combine sales at about one-fourth of production capacity, combine manufacturers are not likely to implement major technological changes in their products in the short term future. This underscores the need for incentives for improved grain quality. A farmer will buy the combine that is best able to meet his quality needs, thereby providing the opportunity for a combine manufacturer to increase market share.

To reduce harvest damage, corn should not be harvested until below 26 % moisture and ideally in the 20 to 24 % range with 20 % being preferred. Soybeans should be harvested in the 13 to 15 % moisture range after first drying down to 13.5%.

Acceptable threshing losses for corn are 0.2 to 0.5 bu/A and for soybeans 0.1 bu/A. Total combine losses including the header should be in the 0.6 to 2.5 bu/A range for corn and no more than 1.1 bu/A for soybeans. Optimal combine settings for least machine loss and least grain damage are not mutually exclusive, but both require good operator skills and ability to take the time to check grain tank samples and losses from behind the combine.

In field studies of corn harvested between 1969 and 1984, BCFM generally ranged between 0.5 and 1 %. The higher levels of BCFM occurred when harvesting at moistures above 20 %. Severe pericarp damage (broken kernels, with large cracks, or pieces of endosperm missing) amounts to about 4 to 12 %. The 12 % severe damage occurred at moistures above 26 %. Other pericarp damage reported as hidden damage, minor damage, internal cracks, hairline cracks, missing pericarp, etc. was up to 40 %. This type of damage was also more prevalent at higher harvest moistures. Samples high in either or both types of pericarp damage tended to have high Stein breakage susceptibility values. Also, high pericarp damage usually results in lower test weights.

Most people would agree that it is desirable to reduce combine damage. But damage is continually defined differently by different people. Damage could mean breakage, crackage, BCFM, cracks and brokens, pericarp damage, severe or minor pericarp damage, hidden pericarp damage, internal cracks, stress cracks, external cracks, hairline cracks, missing pericarp, missing endosperm, or missing tip caps. The only term that shared commonality between studies was BCFM (and that may not have been because some may not have picked the FM on top of the 12/64 in. sieve.)

My recommendation to the Office of Technology Assessment is that a standardized test method for measuring and defining pericarp damage in corn is needed. A standardized test is the only means by which any future reductions in pericarp damage can be determined.

In field studies of soybean harvesting, splits were less than 4 %. Statistically significant reductions in splits were obtained using rotary combines. Rotary combines create fewer splits when rotor speed is set too high than do conventional cylinder combines. This finding indicates rotary combines have a wider range of acceptable speeds; thus, they would be easier for the operator to adjust. Up to about 0.6 to 1.4 percentage points of the splits are attributable to the grain handling system after threshing.

FM in soybeans is commonly below 0.5 % for clean fields with standing beans. In weedy conditions or in lodged beans, FM will be higher and more difficulty is experienced in threshing, separating, and cleaning.

Seedcoat cracks in one study ranged from 3.9 to 5.8 % with lower levels obtained with a rotary combine. Another study indicated about 50 % seedcoat cracks with no differences found between combine types. A third study found 10 % visual damage. Thus, a standardized test for seedcoat cracks is also needed to provide common definitions.

Future technology for improving corn and soybean quality should be aimed toward helping the farmer or combine operator to better understand the threshing, separating, and cleaning functions of his combine. Biosensors measuring crop properties and monitoring sensors for helping set the combine for minimum damage and losses are also needed. More use of computer algorithms can help operators understand the effects of combine settings on grain damage. Research for the development of algorithms to use for computerized control of areas such as ground speed, feeder speed, cylinder/rotor speed, concave clearance, sieve openings, and fan speed is needed.

Finally, incentives for improved quality are needed. So far, farmers' pride and rather remote and indirect incentives are all that is available. For example, less FM reduces drying and aeration costs. It can be observed that combines do quite well on the well-defined factors such as BCFM, splits, and FM in clean beans. It is on the unclearly defined factors like pericarp damage and seedcoat cracks, that considerable damage is apparent. A first step in reducing this damage would be to develop standardized tests followed by incentives to achieve low levels of pericarp or seedcoat damage.

The incentive for some farmers to deliver low levels of pericarp damage in corn may be only pennies per bu, because reductions in pericarp damage by 50 % can be achieved simply by waiting until about 20 % moisture to harvest. A farmer needs enough incentive to offset the risk of higher field losses due to waiting.

Research is needed to determine actual value of reduced pericarp damage for different corn varieties for end uses such as wet milling, dry milling, snack food processing, feed manufacturing, and livestock feeding. It is only with defined values for improved quality of corn and soybeans, and objective measures of quality, that harvesting technology and operator management can respond by producing improved quality of U.S. corn and soybeans.

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APPENDIX

Table 1. U.S. Corn Production and Harvested Acreages by Year.

Year	Acres Harvested x 1000	Production bu x 1000	Average Yield bu/acre	Production t x 1000
1960	71,422	3,906,949	54.7	99,212
1961	57,634	3,597,803	62.4	91,361
1962	55,726	3,606,311	64.7	91,577
1963	59,227	4,019,238	67.9	102,063
1964	55,369	3,484,253	62.9	88,478
1965	55,392	4,102,867	74.1	104,187
1966	57,002	4,167,608	73.1	105,831
1967	60,694	4,860,372	80.1	123,422
1968	55,980	4,449,542	79.5	112,990
1969	54,574	4,687,057	85.9	119,021
1970	57,358	4,152,243	72.4	105,440
1971	64,123	5,646,260	88.1	143,379
1972	57,513	5,579,832	97.0	141,692
1973	62,143	5,670,712	91.3	144,000
1974	65,405	4,701,402	71.9	119,386
1975	67,625	5,840,757	86.4	148,318
1976	71,506	6,289,169	88.0	159,705
1977	71,614	6,505,041	90.8	165,186
1978	71,930	7,267,927	101.0	184,559
1979	72,400	7,928,139	109.5	201,324
1980	72,961	6,639,396	91.0	168,598
1981	74,524	8,118,650	108.9	206,162
1982	72,719	8,235,101	113.2	209,119
1983	51,483	4,174,678	81.1	106,010
1984	71,915	7,674,020	106.7	194,871
1985	75,134	8,865,006	118.0	225,114

Source: USDA Agricultural Statistics, 1986. U.S. Government Printing Office, Washington D.C. 20402.

Table 2. U.S. Soybean Production and Harvested Acreages by Year.

Year	Acres Harvested x 1000	Production bu x 1000	Average Yield bu/A	Production t x 1000
1960	23,655	555,085	23.5	15,104
1961	27,003	678,554	25.1	18,464
1962	27,608	669,186	24.2	18,209
1963	28,615	699,165	24.4	19,025
1964	30,793	700,921	22.8	19,073
1965	34,449	845,608	24.5	23,010
1966	36,546	928,481	25.4	25,265
1967	39,805	976,439	24.5	26,570
1968	41,391	1,106,958	26.7	30,121
1969	41,337	1,133,120	27.4	30,833
1970	42,249	1,127,100	26.7	30,669
1971	42,705	1,176,101	27.5	32,003
1972	45,683	1,270,608	27.8	34,574
1973	55,667	1,547,543	27.8	42,110
1974	51,341	1,216,287	23.7	33,096
1975	53,617	1,548,344	28.9	42,132
1976	49,401	1,288,608	26.1	35,064
1977	57,830	1,767,267	30.6	48,089
1978	63,663	1,868,754	29.4	50,850
1979	70,343	2,260,665	32.1	61,515
1980	67,813	1,797,543	26.5	48,913
1981	66,163	1,989,110	30.1	54,125
1982	69,442	2,190,297	31.5	59,600
1983	62,525	1,635,772	26.2	44,511
1984	66,113	1,860,863	28.1	50,636
1985	61,584	2,098,531	34.1	57,103

Source: USDA Agricultural Statistics, 1986. U.S. Government Printing Office, Washington D.C. 20402.

Table 3. Numbers of Combines Sold in the U.S. by Class and Year.

Year	Self-propelled combines							Pull-type Combines	Total of all Combine Types
	Class								
	1	2	3	4	5	6	Total		
1986			616	1,899	3,420	1,725	7,660	21	7,681
1985			792	2,132	3,702	1,785	8,411	51	8,462
1984			1,118	3,126	4,890	2,288	11,422	88	11,510
1983			1.507	3,818	5,257	2,169	12,751	106	12,857
1982			2,011	4,499	6,768	2,927	16,205	176	16,381
1981			4,223	8,462	10,496	3,650	26,831	364	27,195
1980			4,102	8,443	10,384	2,812	25,741	461	26,202
1979			6,570	11,671	14,005		32,246	674	32,920
1978							31,494	17	31,511
1977							28,813		28,813
1976							32,519		32,519
1975		2,965	9,420	12,590	6,100		31,075		31,075
1974							31,595		31,595
1973							35,082	33	35,115
1972							28,567	666	29,233
1971	1,393	5,810	8,563	9,023	2,458		27,247	695	27,942
1970	2,036	5,988	8,949	9,731			26,704	584	27,288
	$ Value								
	<8000	<10000	<11500	>11500					
1969	3,221	7,045	8,888	7,946			27,100	951	28,051
1968	5,349	8,526	12,071	7,561			33,507	1,338	34,845
	<7500	<9000	<11000	>11000					
1967	9,060	10,964	15,228	5,437			40,689	1,587	42,276
	Header Width, ft.								
	<12	12-14	14-16	16-20	>20				
1966	826	10,666	8,831	8,162	11,326		39,811	2,041	41,852
1965	1,381	12,470	8,441	7,117	8,198		37,607	2,323	39,930
1964		12,660	7,226	7,736	3,130		30,752	2,770	33,522

Source: Farm and Industrial Equipment Institute, Annual Retail Sales Reports issued February of each year from 1987 through 1965. Chicago, IL. 60611.

Table 4. Numbers of Cornpickers Sold in the U.S. by Year.

Year	Number of Rows			
	1 all	2-3 pull	2 mounted	Total
1974				6,673
1973	77	188	106	8,974
1972	2,502	3,593	1,878	7,973
1971	3,044	3,564	2,362	8,970
	1 mounted	2 pull	2 S.P.	
1970	2,724	3,124	2,679	8,527
	1 S-P			
1969	3,107	3,515	3,681	10,303
1968	3,441	3,878	4,808	12,127
1967	4,278	3,614	5,969	13,861
	1	2 pull	2 mounted	
1966	4,058	3,601	7,013	14,672
1965	4,622	3,855	8,601	17,078
	1 pull, mtd, S.P.	2 pull	2 mounted or S.P.	
1964	4,123	3,381	8,042	15,546

Source: Farm and Industrial Equipment Institute, Annual Retail Sales Reports issued February of each year from 1987 through 1965. Chicago, IL. 60611.

Table 5. Numbers of Cornheads Sold in the U.S. by Year.

Year	Number of Rows					Total	Percent of combines sold with cornheads
	2	3	4	5 & 6	7&over		
1986	0	49	1,469	2,564	634	4,716	61.57
1985	30	30	1,617	2,707	632	5,016	59.64
1984	36	30	2,188	3,378	787	6,419	56.20
1983	64	47	2,551	3,393	775	6,830	53.56
1982	116	105	3,789	4,226	1,058	9,294	57.35
1981	208	230	6,551	7,053	1,658	15,700	58.51
1980	315	365	7,772	7,141	1,561	17,154	66.64
1979	394	610	11,502	8,342	1,526	22,374	69.39
1978						21,196	67.30
1977						20,641	71.64
1976						25,440	78.23
1975	2,247	1,828	14,735	5,764	738	25,312	81.45
1974						25,156	79.62
1973						26,705	76.12
1972	4,603	2,234	11,652	2,641	0	21,130	73.97
1971	5,401	2,606	10,560	2,248	0	20,815	76.39
				6 or more			
1970	5,679	2,773	8,331	1,759		18,542	69.44
1969	6,759	2,905	6,131	1,078		16,873	62.26
1968	9,119	3,829	6,098	989		20,035	59.79
			4 or more				
1967	13,622	4,272	7,900			25,794	63.39
1966	15,000	3,365	6,166			24,531	61.62
1965	17,969	992	3,925			22,886	60.86
		3 or more					
1964	15,088	2,010				17,098	55.60

Source: Farm and Industrial Equipment Institute, Annual Retail Sales Reports issued February of each year from 1987 through 1965. Chicago, IL. 60611.

Table 6. List of Self-Propelled Combine Models by Class Sold in the U.S. in 1987

	Class				
	1 and 2	3	4	5	6
Maximum Grain Tank Capacity, bu		125	180	200	310
Maximum Concave Area, in^2		978	1421	1421	2496
Approximate Average Maximum Capacity in Wheat, bu/hr		—	—	240-380	320-560
Manufacturer					
Case-IH		**1420*** **1620**	**1440*** **1640**	**1460*** **1660** **1470**	**1480*** **1680** **1682**
Claas		DOM 68	DOM 76 DOM 78	DOM 96 DOM 98	DOM 106 DOM 108 DOM 112CS COM 114CS DOM 116CS COM 116CS
Deere and Co.		4420* 4425	6620 6622*	7720 7722	8820
Deutz-Allis		F3	M3 MH3*	L3 **R5** **M5*** **R50**	**R60** **R6*** **M6*** **R70** **R7*** **M7***
Ford New Holland			**TR76**	**TR85*** **TR86**	**TR95*** **TR96**
Massey-Ferguson	MF8 MF16		550 850	860 855 8560	865 **8590**
New Idea			819		

* Denotes model is being phased out. Bold type indicates rotary threshing mechanism.

Sources: Farm and Industrial Equipment Institute, Annual Model Survey issued March 1987. Chicago, IL 60611;
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Table 7. Acceptable Soybean Harvesting Loss Levels.

		Acceptable Level		
Type of Losses		bu/A*		%
Pre-harvest loss		0.1		0.25
Gathering unit loss		1.1		2.75
a. Shatter	0.4		1.00	
b. Loose Stalk	0.2		0.50	
c. Lodged Stalk	0.2		0.50	
d. Stubble	0.3		0.75	
Threshing and separating loss		0.1		0.25
Total crop loss		1.3		3.25

* Assumes a soybean yield of 40 bu/A. From D.M. Byg "Guidelines for expert soybean harvesting", Bulletin 578. Cooperative Extension Service, Ohio State University, Columbus, Ohio.

Table 8. Acceptable Corn Harvesting Loss Levels.

Type of Loss		Acceptable Level bu/A* or %+
Gathering unit loss		0-1
Loose kernel loss		0.4-1
a. Snapping roll	0.2-0.5	
b. Separation	0.2-0.5	
Threshing loss		0.2-0.5
Total machine loss		0.6-2.5

---

* Assumes corn standing 90% or better and a moisture of 20 to 26%. From D.M. Byg "A Guide for Measuring Corn Harvest Losses", AED-108 Extension Pamphlet, Ohio State University.

+ % levels are same as bu/A levels assuming a yield of 100 bu/A.

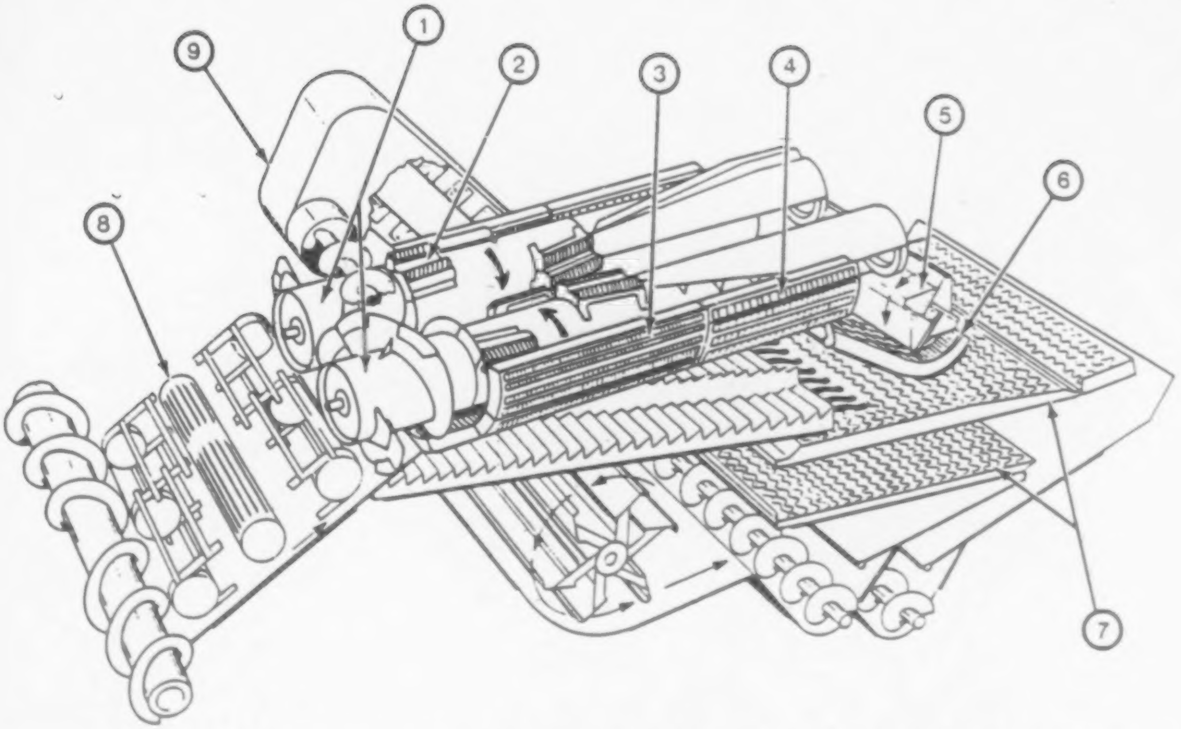


Figure 1. New Holland TR96: (1) Twin Rotors, (2) rasp bars, (3) threshing concave, (4) separating concave, (5) discharge beater, (6) beater grate, (7) cleaning shoe, (8) stone ejection roller, (9) tailings return. Photo from Frehlich et al. (1986), Prairie Agricultural Machinery Institute.

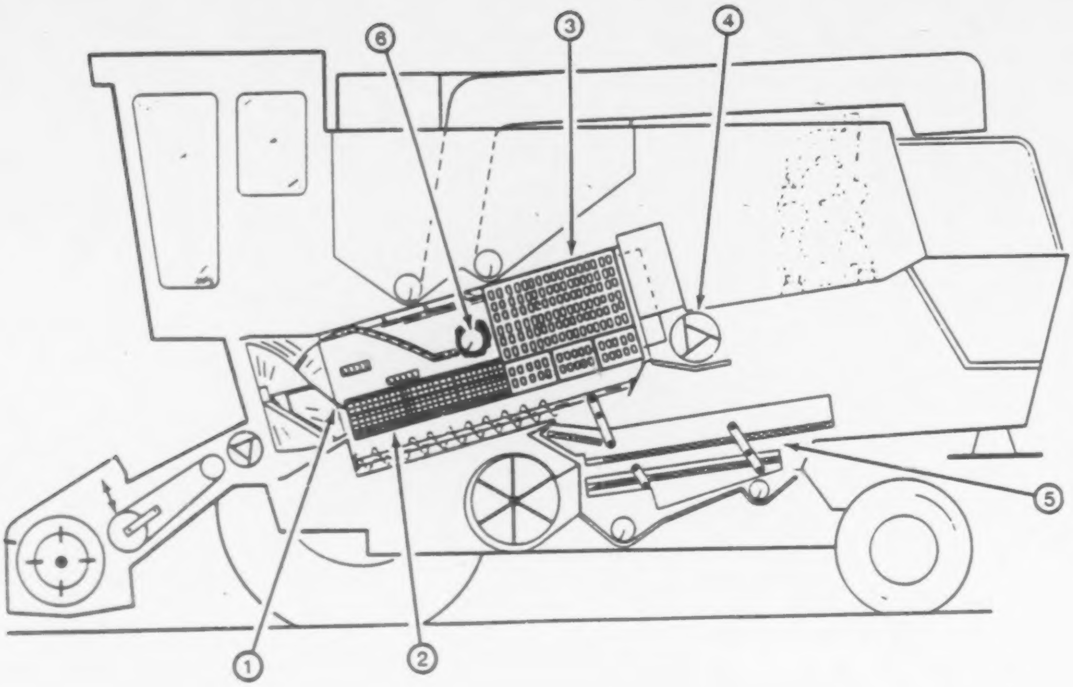


Figure 2. Case IH 1660: (1) rotor, (2) threshing convcaves, (3) separating concaves, (4) back beater, (5) cleaning shoe, (6) tailings return. Photo from Frehlich et al. (1987), Prairie Agricultural Machinery Institute.

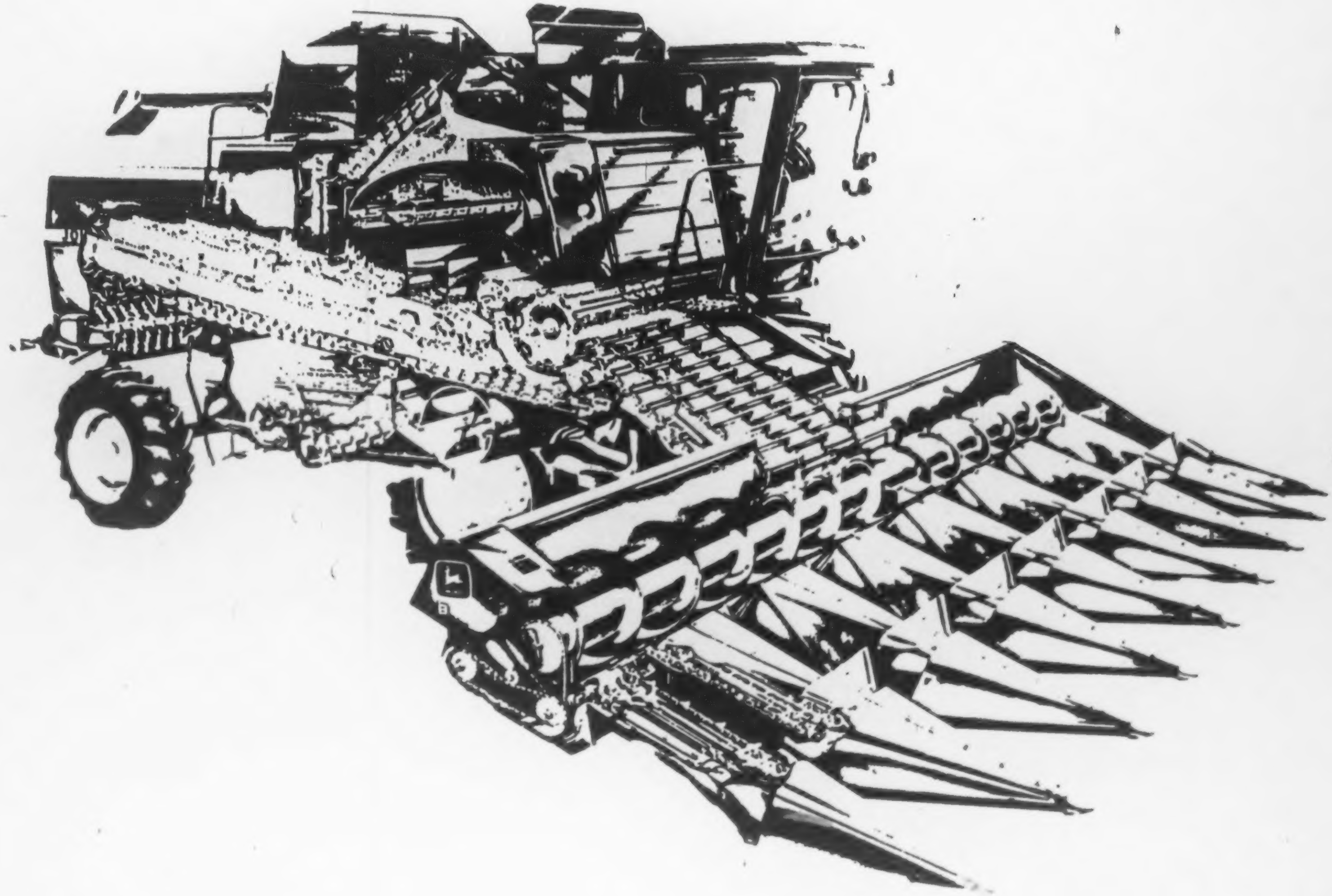
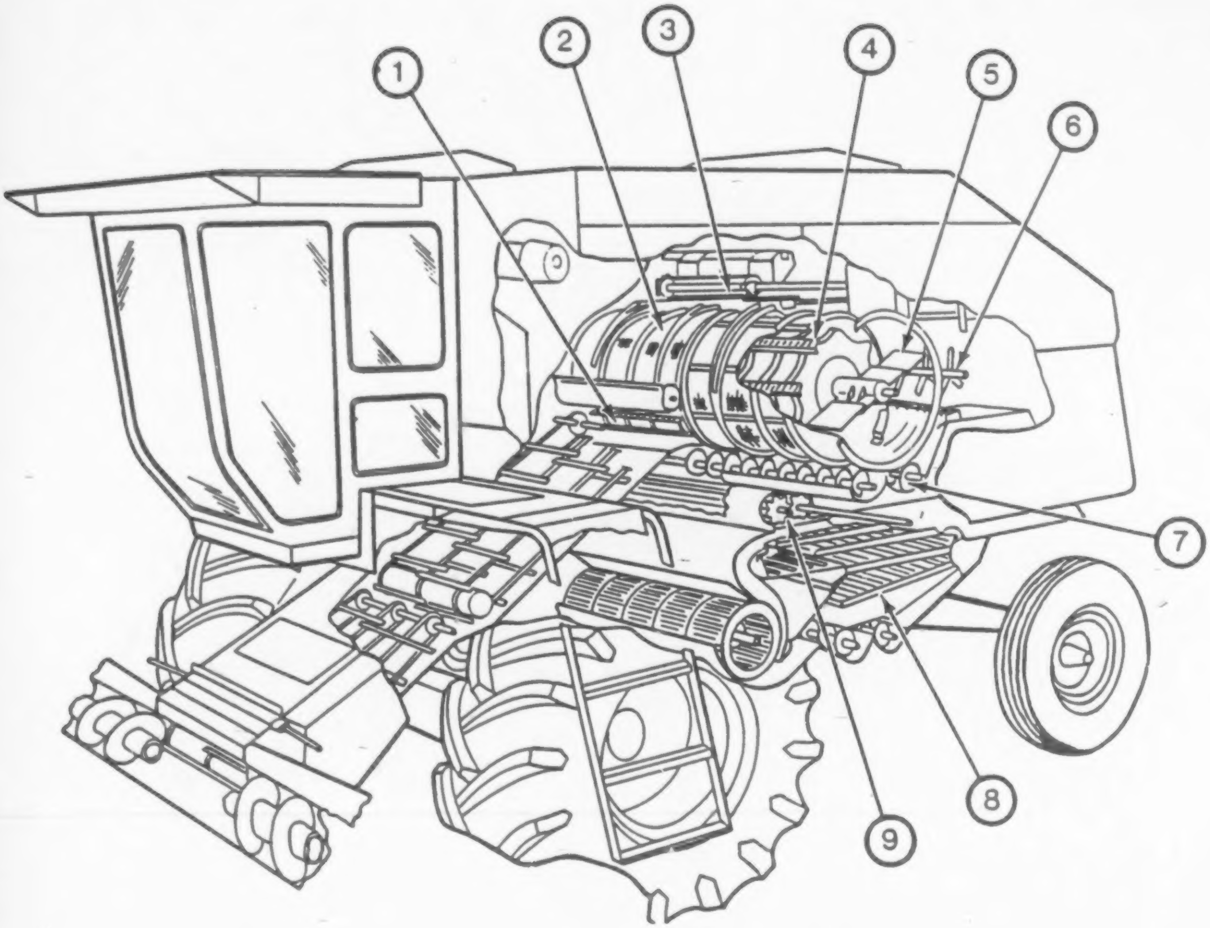


Figure 3. John Deere Titan II combine showing corn head, feeder, cylinder, concave, beater, straw walkers, cleaning shoe, and transfer augers. Photo courtesy of Deere and Co.



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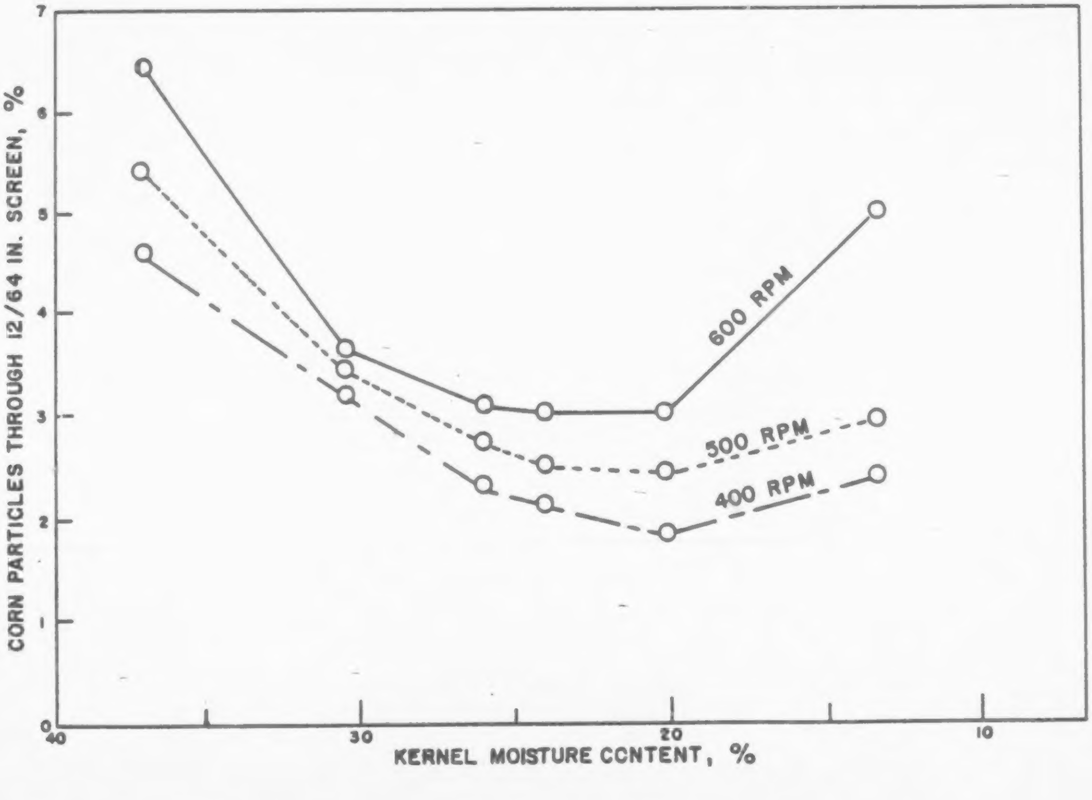

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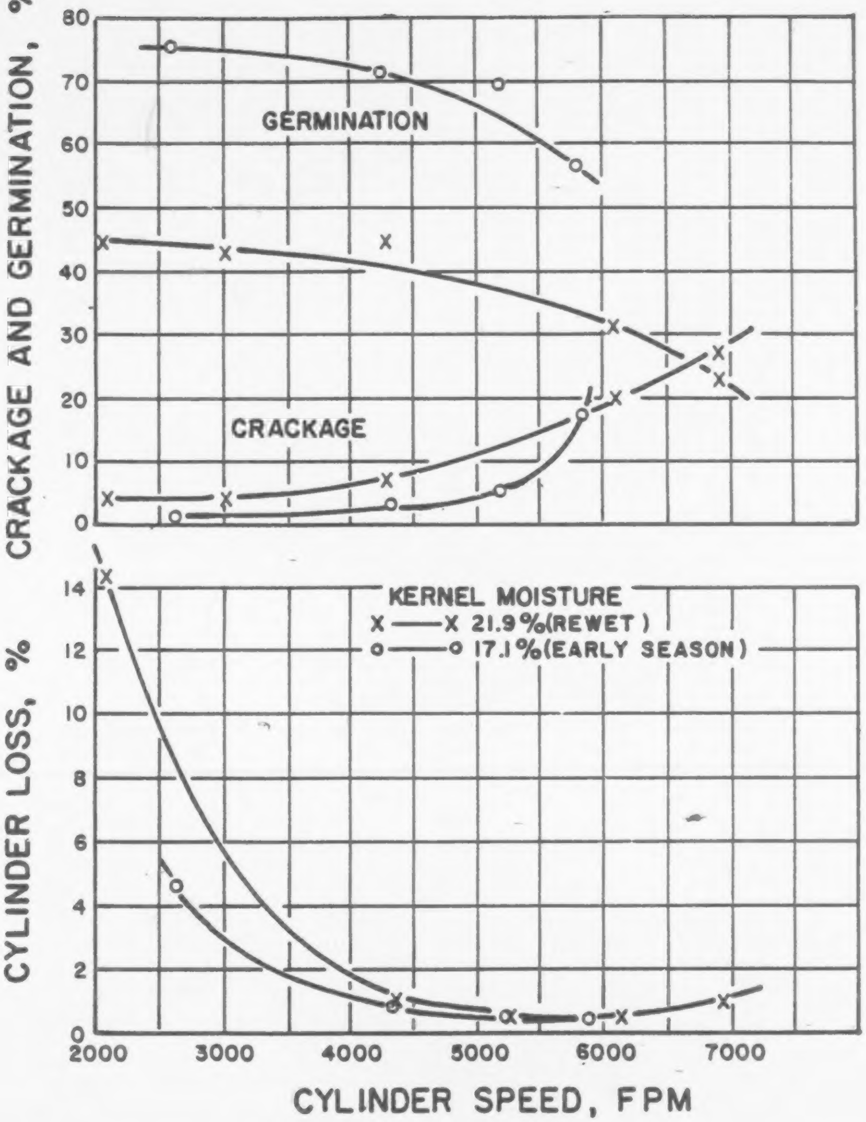

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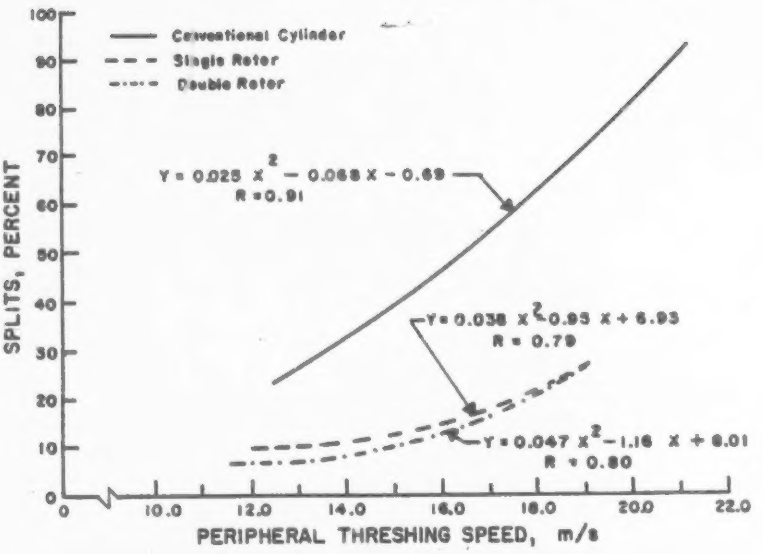

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Background Paper No. 2

Wheat Quality as Influenced by Harvesting Machinery

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March 1989

Office of Technology Assessment
U.S. Congress

This background paper was prepared for the assessment "Enhancing the Quality of U.S. Grain for International Trade." The views expressed are those of the author(s) and not necessarily those of OTA.

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General Introduction

The subject of this report is wheat harvesting technology and its influence on the quality of wheat produced in the United States. Discussion will include methods with which producers can better preserve grain quality using current harvesting technology as well as the grain quality implications of future harvesting developments. The scope of this report includes operations beginning with grain maturity in the field, and ending with grain discharge from the combine.

Current State of the Art

Function of Combine

Nearly all of the wheat produced in the United States is harvested by a grain combine. Most commonly, a self-propelled combine equipped with a direct-cut header is used to cut standing wheat, process it, and deliver it to a bulk bin in a condition acceptable for marketing. While differences exist between various combine designs, five basic functions are performed on the crop. The nomenclature for combine components varies somewhat with the design, so where appropriate, American Society of Agricultural Engineers standard terminology (ASAE, 1987) will be used. The five functions of the combine are:

1. Cutting and feeding: The crop is first cut and conveyed to the processing sections of the combine. Direct-cut headers gather the top portion of the wheat plant into the combine

directly, with no intermediate operations. The functional components of the grain header include a reel to control initial crop motion, a reciprocating sickle to cut the crop, and a large rotating auger equipped with timed, and retractable fingers to convey the crop to the feeder house of the combine.

2. Threshing: Next, the crop is threshed to dislodge the grain from the head. This process is performed by a rotating cylinder and stationary concave (items 1 and 2, figure 1-1) with a conventional combine, or by a rotor and concave on rotary machines (items 1 and 2, figure 1-2). An important secondary function of the cylinder/rotor is to separate the grain from the larger plant parts. This is accomplished by the use of a grate-type concave which allows the passage of grain and small plant parts, but not long straw. The grain and other material that passes through the concave is fed by augers (figures 1-1, 1-2) or an oscillating grain pan (figure 1-3) to the cleaning shoe for final cleaning.
3. Separation: Separation refers to the removal of loose grain from the straw and other plant parts. In a conventional combine, separation begins with a large portion of the grain passing through the cylinder concave. Further separation is performed by a rotating beater located immediately behind the cylinder (item 3, figure 1-1), which agitates the crop mass and allows additional grain to pass through a

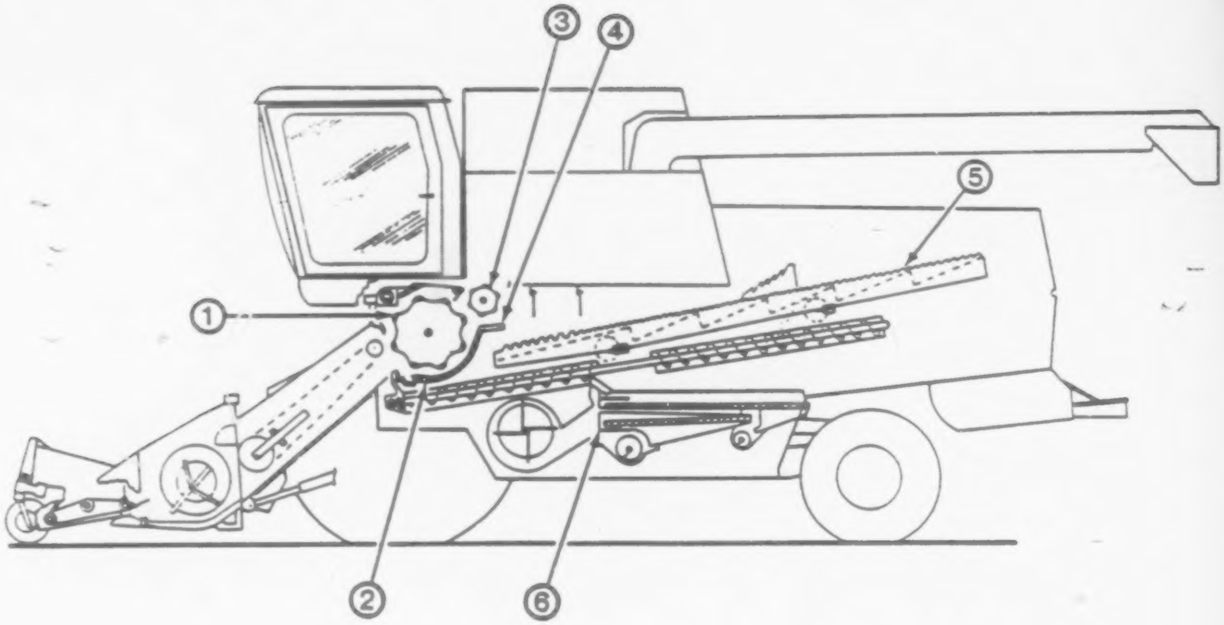

Figure 1-1. Conventional combine, equipped with window pickup header: (1) cylinder, (2) concave, (3) beater, (4) beater grate, (5) straw walkers, (6) shoe. From Frehlich et al. (1985), Prairie Agricultural Machinery Institute.

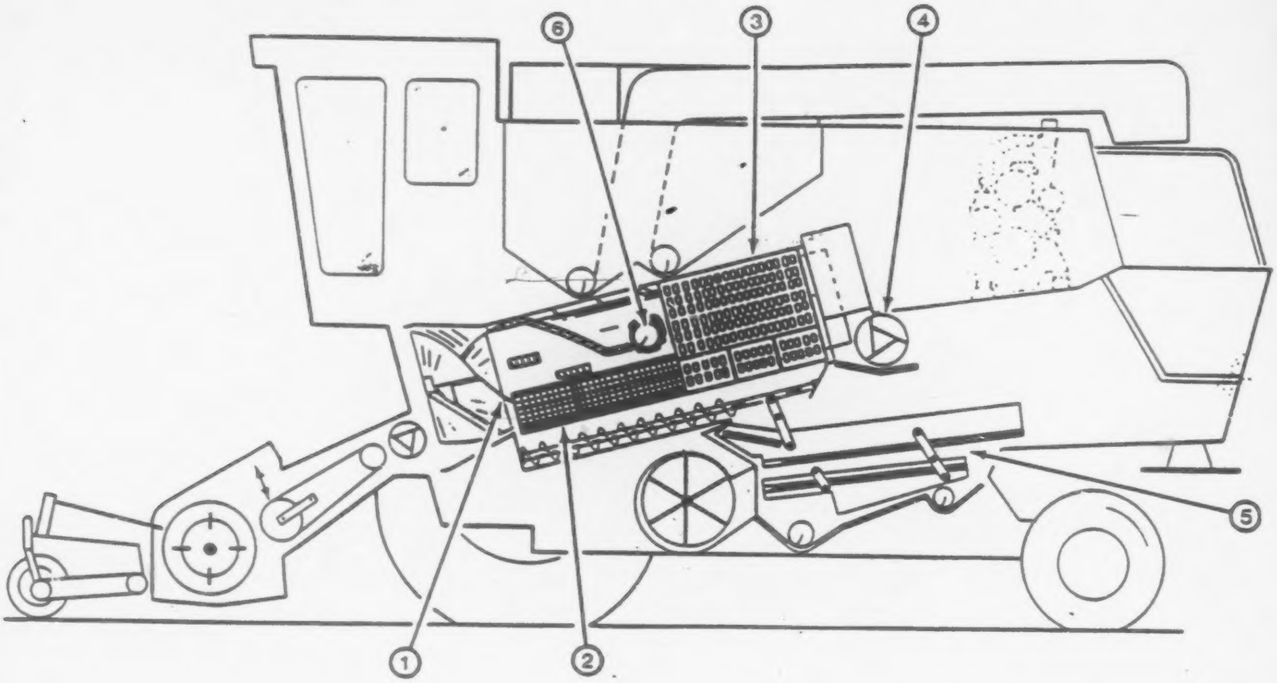

Figure 1-2. Single rotor rotary combine: (1) rotor, (2) threshing concaves, (3) separating concaves, (4) rear beater, (5) shoe, (6) tailings return. From Frehlich et al. (1987), Prairie Agricultural Machinery Institute.

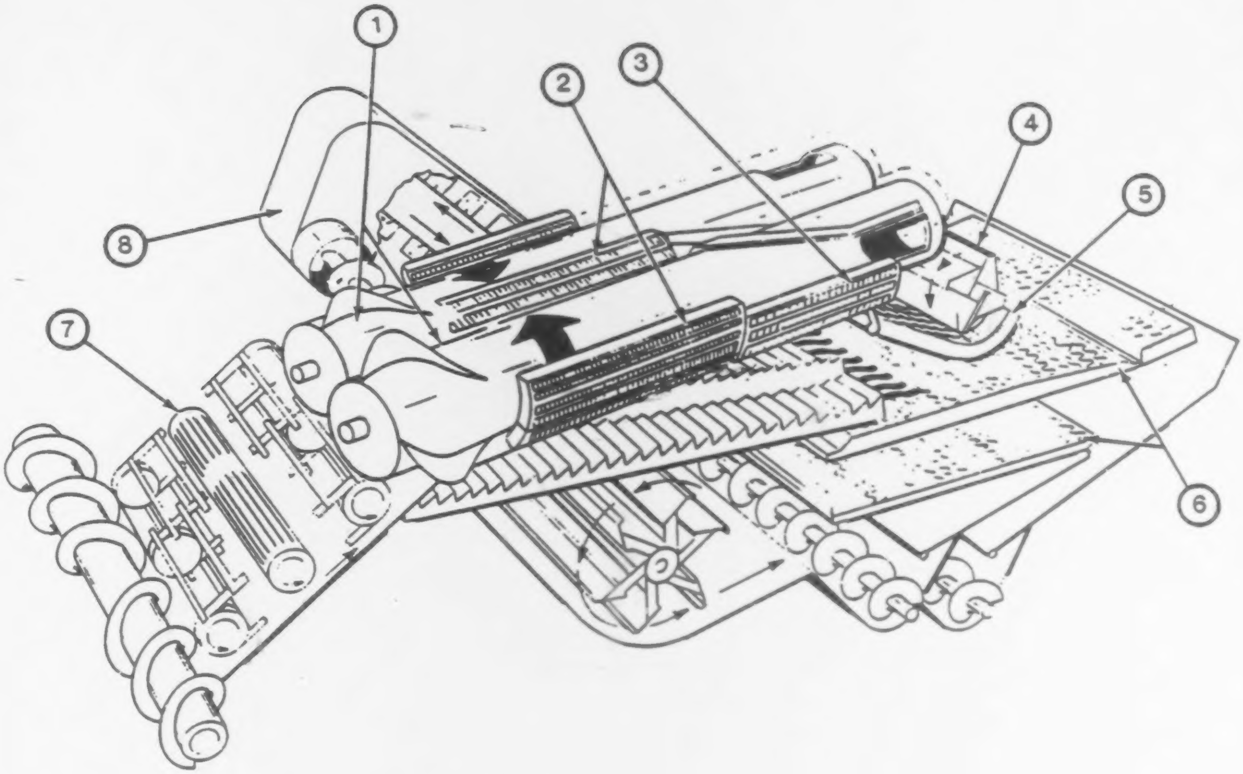

Figure 1-3. Functional components of twin rotor combine: (1) rotors, (2) threshing concaves, (3) separation concaves, (4) discharge beater, (5) beater grate, (6) cleaning shoe, (7) stone ejection roller, (8) tailings return. From Frehlich et al. (1984), Prairie Agricultural Machinery Institute.

transition grate (or beater grate). Separation is completed by the straw walkers (item 5, figure 1-1) on a conventional combine. In a rotary combine, separation is performed by the rear part of the rotor, and is sometimes assisted by a beater and grate located behind the rotor (items 4 and 5, figure 1-3).

4. Cleaning: Cleaning may be regarded as the final stage of separating grain from fine plant parts, weed seeds, soil, or other foreign material. Cleaning is the last process performed on the grain prior to delivery to the clean grain bin of the combine. On most combines, cleaning is performed by a component called the "cleaning shoe" (item 6, figure 1-1), which generally consists of two adjustable louver-type sieves which oscillate and are assisted by upward air flow through them. The top sieve is commonly called the chaffer sieve, while the bottom sieve is called the cleaning sieve. Grain which passes through both sieves is conveyed directly to the clean grain bin, while material which passes through only the top sieve is returned to the cylinder for rethreshing and subsequent cleaning.

5. Grain Handling: Crop handling is the final function performed by a combine, and the mechanism used to convey the crop depends on the status of the crop. Unthreshed material is usually conveyed by chain-and-slat conveyors or rotating

paddle-type conveyors. Clean grain is usually handled by a combination of augers or paddle elevators.

Variations of Combine Design and Function

The most common machine for performing the above five functions is a conventional self-propelled combine. Variations of the system include the development of rotary combines, the practice of windrowing the grain prior to combining, and the development of sidehill and hillside combines.

1. Rotary Combines. During the 1970's, many North American combine manufacturers introduced rotary combines. Rotary machines differ from conventional combines in that the cylinder, beater, and straw walkers of the conventional machine are replaced by a rotor, or pair of rotors.

   Rotary combines may have the rotor oriented axially (figures 1-2, 1-3) or transversely (figure 1-4) within the combine. Axial rotor machines may be equipped with either one or two rotors. The crop is introduced into the rotor and moves in a helical fashion along the axis of the rotor. Threshing and separation functions both occur while the crop resides between the rotor and concave, and the distinction between the two functions is not as clear as with the conventional machines. Rotary designs give the crop repeated exposure to the permeable grates, which, in addition to the high radial accelerations that exist within the crop mass

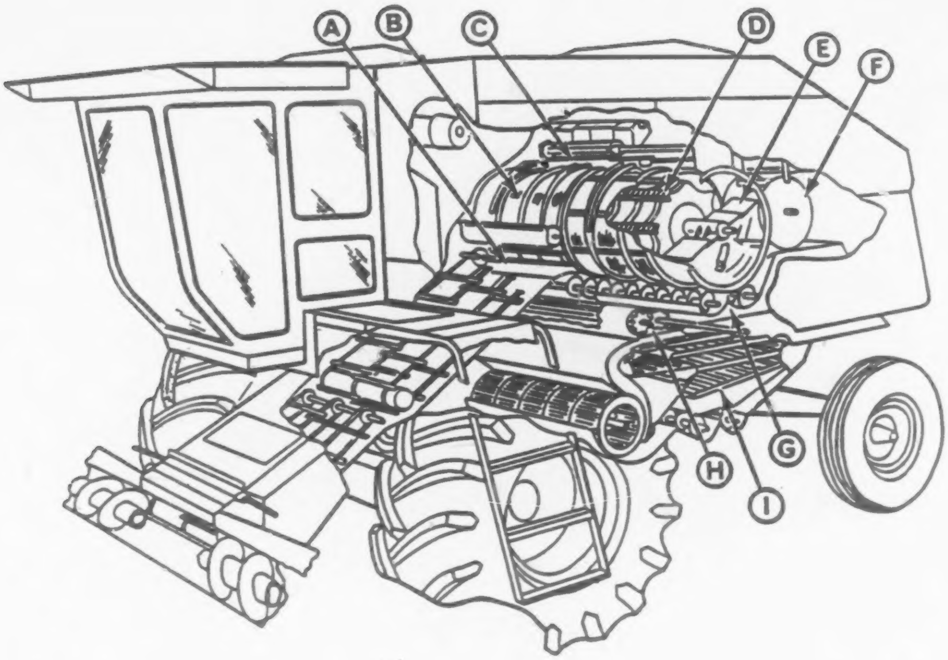

Figure 1-4. Rotary combine with transverse rotor: (A) concave, (B) cage, (C) cage sweeps, (D) rotor, (E) discharge paddles, (F) discharge beater, (G) distribution augers, (H) accelerator rolls, (I) cleaning shoe. From Myborg et al. (1981), Prairie Agricultural Machinery Institute.

(Rowland-Hill, 1975), enables separation to occur in a more compact volume than with conventional combines.

The primary factor which has driven the development of rotary combines is the grain loss behavior of straw walkers, along with the demand for more capacity within a compact, transportable, machine. In wheat, conventional straw walkers exhibit an exponential rise in grain loss as the MOG (material other than grain) feedrate is increased (figure 1-5). Although this principle has been known for many years (Nyborg et al., 1969), until the early 1970's, the desired combine capacities could be achieved with acceptable overall size by using conventional combine technology. At that point, basic machine shipping weights were approaching 10000 kg, and there were still demands for more capacity.

Compared to conventional combines, rotary combines usually exhibit a more gradual increase in loss as feedrate is increased (figure 1-6), so the maximum capacity of a rotary machine is often dictated by power or crop feeding limitations, rather than loss. Figures 1-5 and 1-6 cannot be compared directly, since the tests were conducted under different conditions. However, the graphs illustrate the basic shapes of the loss curves.

One result of changing to rotary technology has been an increase in capacity for a given physical size of combine. DePauw et al. (1977) stated that a conventional combine

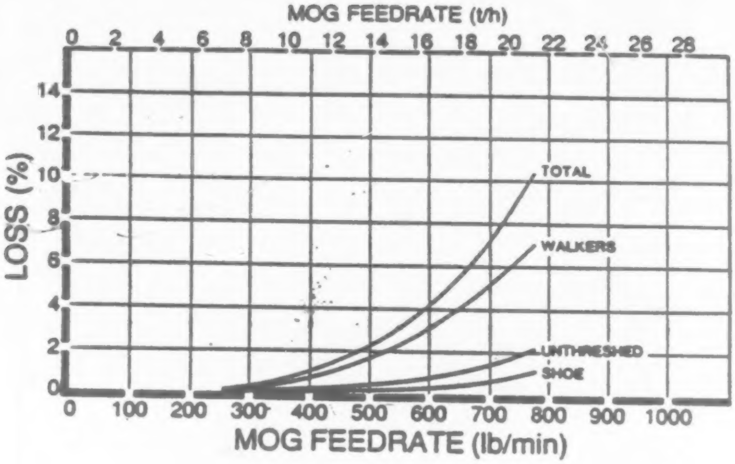

Figure 1-5. Loss characteristics of a class 5 conventional combine in wheat, showing walker, unthreshed, and shoe losses. From Frehlich et al. (1985), Prairie Agricultural Machinery Institute.

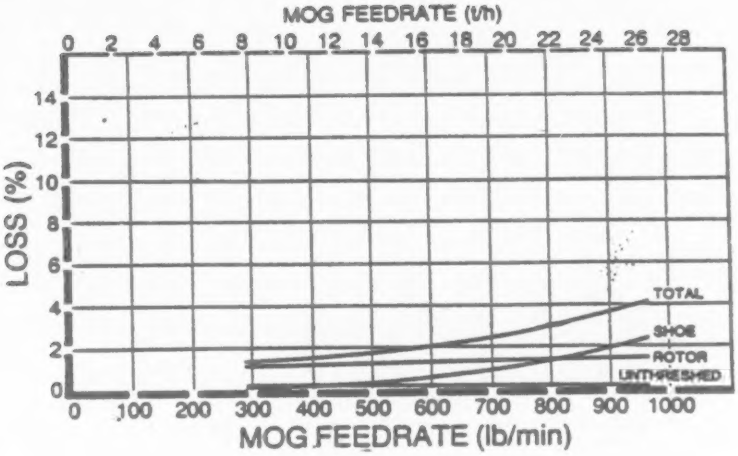

Figure 1-6. Loss characteristics of a class 5 rotary combine in wheat, showing rotor, unthreshed, and shoe losses. From Frehlich et al. (1987), Prairie Agricultural Machinery Institute.

capable of harvesting 30000 lb/hr of wheat would require a threshing and separator unit 181" long by 48" wide, while a comparable rotary processing unit would require only 104" x 36".

2. Grain Windrowing. Most U. S. wheat is harvested with direct cut headers, but a separate windrowing operation is still practiced on significant spring wheat acreage in the northern plains. Windrowers cut the wheat and place it in a swath on top of the wheat stubble, where it is later harvested by a combine equipped with a windrow pickup device (figures 1-1, 1-2). The windrower is usually equipped with a draper-type header, which offers gentler handling than the auger-type headers usually used on hay windrowers. Windrowing usually begins when the wheat is in the 30-35% moisture content range (Quick and Buchele, 1978). Although windrowing is an additional expense, the following reasons have been given as justification:

   a. Weed infestations, which are usually in a stage of rapid growth as the wheat ripens, can be dried with the wheat in the windrow. The fact that the wheat is windrowed relatively early can interrupt the development of viable weed seed, thereby improving weed control in subsequent years.

b. The windrowing of the crop can speed wheat drying by up to two weeks, allowing more reliable harvest timing and better use of the short growing season.

c. While in the windrow, the crop may be in a better position to withstand hail and high winds than when standing.

d. Many windrowers are equipped to place two windrows side-by-side when cutting a thin crop of wheat, creating forty to sixty foot windrow spacing. This practice can shorten combining time considerably.

3. Hillside and Sidehill Machines. Combine performance is adversely affected by slopes, whether they be side slopes or fore-and-aft. This is particularly true of those components on the combine, such as the cleaning shoe, that depend on gravity to perform their function. One test found that a conventional combine in wheat had its capacity at 2% loss reduced by approximately 35% when operating on a side slope of 18% (Quick and Buchele, 1978).

In the Pacific Northwest, slopes of 40 percent are tilled, with occasional firm soils being tilled up to 70% slope. In the past, combines have been available with leveling in both pitch and roll modes. However, the usual procedure is for farmers to cut their fields across slope, although passes up and down slope are necessary when opening fields. Thus, current hillside combine models feature up to

48% leveling in the roll mode, but little or no pitch leveling (Pickett et al., 1980). Such machines are heavily modified production combines, with unique suspensions, drive lines, and feeder house modifications.

In the mid-1970's, the sidehill combine, equipped with only roll leveling, was developed for use on sideslopes up to 20%. It was intended primarily for the moderately rolling terrain of the midwest.

Interaction of Harvesting Technology With the Grain Handling System

Grain Damage and the Threshing Process

Grain damage occurs primarily in the threshing process of a combine, although the augers used for grain handling on the combine can also contribute to damage. The factors having the greatest effect on grain damage are cylinder adjustments, the type of threshing mechanism, and crop properties.

Cylinder Adjustments: Cylinder speed is regarded as the most important machine parameter affecting grain damage (Kepner et al., 1978), and as cylinder speed is increased, grain damage increases exponentially. As shown in figure 1-7, an increase from 26 m/s to 29 m/s cylinder peripheral speed increased damage from 2% to 4% on wheat having a 14.6% moisture content. However, unthreshed grain left in the head is reduced as speed is

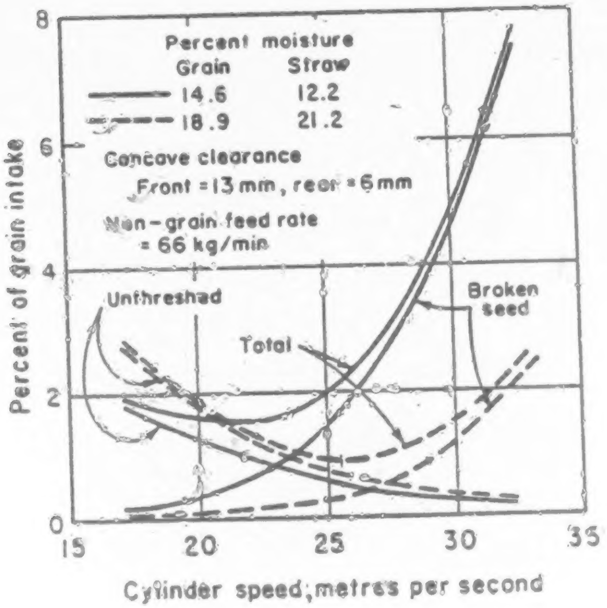

Figure 1-7. Effect of cylinder speed upon seed damage and cylinder loss in laboratory tests with wheat, using a cross-flow rasp-bar cylinder. From Kepner et al. (1978).

increased, which leads to a compromise in the setting. Figure 1-7 indicates an optimum setting of about 23 m/s speed for 14.6% moisture and 26 m/s speed for 18.9% moisture wheat, if the economic losses due to grain damage and unthreshed grain are equal. Normally, grain damage is a smaller economic loss than unthreshed grain, leading to slightly higher optimum cylinder speeds.

Kepner et al. (1978) states that threshing can be accomplished by impact of a fast moving member upon the material, rubbing, squeezing of pods, or some combination of these actions. Wrubleski and Reed (1980) performed high speed photography of the threshing process that occurred in both standard and modified cylinders and concaves. They concluded that in wheat, most of the threshing is caused by the impact of the cylinder rasp bars on the grain heads, rather than friction.

Cylinder-concave clearance has a greater influence on unthreshed loss than on grain damage. Kepner (1978) reported tests in which a reduction from 19 mm to 6 mm cylinder clearance reduced cylinder loss from 2.1% to 1.2%, while increasing visible damage from 5.4% to 7.8%. Reducing cylinder clearance can generally achieve a given reduction in cylinder loss with less increase in grain damage than if cylinder speed were increased.

Due to variations in crop conditions, cylinder-concave settings are usually published as ranges in combine operator's manuals, placing on the operator the responsibility of determining the most appropriate settings for a specific field of crop. A given level of threshing efficiency can usually be obtained at several combinations of cylinder speed and cylinder-concave clearance. In view of the influence of cylinder speed on grain damage, it is apparent that operators can reduce grain damage by opting for a lower speed-smaller clearance setting within the constraints of the factory recommendations.

There has been considerable publicity in wheat production areas of the United States and Canada regarding the modification of conventional combines. The modifications most commonly promoted are:

- The concave bars are built up to 8 mm above the concave wires, and machined to nearly constant radius only slightly larger than the cylinder.
- Some of the concave openings are blocked.
- Some of the concave wires are removed.
- The cylinder-concave clearance is set at nearly zero at the rear and 8 mm at the front for all crops.

Wrubleski and Reed (1980) made a detailed comparison of the performance of a standard and modified combine, examining walker losses, shoe losses, unthreshed losses, and grain damage. Although there were trade-offs between cylinder separation and walker separation, the loss performance of both machines was very similar in wheat. Grain damage, however, was higher for the modified combine than for the standard machine when operated in tough Neepawa wheat. Foreign material remaining in the wheat was an average of 2.1% for the modified combine and 0.4% for the standard machine. The study concluded that the modifications increased foreign material with no increase in capacity and therefore should be avoided.

Type of Threshing Mechanism: Several reports have concluded that rotary combines produce substantially less grain damage than conventional combines when harvesting wheat. Fairbanks et al. (1978) conducted field tests of rotary and conventional combines in wheat. In 12 replicated side-by-side comparisons, the rotary machine produced significantly less crackage in every case. The average crackage for all tests was 0.88% for the rotary and 2.25% for the conventional machines.

Others have reported similar reductions in crackage using rotary machines. Murray, et al. (1977) reported 1/3 as much crackage in the first generation Axial-Flow rotary combine. Rowland-Hill (1975) also reported lower grain damage with a rotary machine. He attributed the lower damage levels to the fact that more time elapses between impacts of the rasp bars on the crop mass, while both centrifugal acceleration and air turbulence tend to quickly move threshed grain through the separation grates.

Crop Properties: Within the range of moisture contents typically harvested, higher grain moisture content tends to reduce grain damage. Again referring to figure 1-7, a difference of about 1.5% grain damage is apparent between 14.6% and 18.9% moisture wheat, threshed by a cylinder with a 25 m/s peripheral speed. Since grain damage becomes more serious at lower moisture contents, cylinder speeds should be reduced when harvesting dry grain.

The maximum moisture at which wheat is harvested is usually determined by constraints within the storage, handling, and marketing system. Many factors encourage a producer to complete wheat harvest as soon as possible, among them field shatter, test weight losses, and a marketing system which remits no compensation for dry (below approx. 14%) wheat. The increase in grain damage that occurs at low moisture conditions is thus one additional factor which encourages timely harvest.

Summary on Wheat Damage: The following factors can be controlled to have a positive influence on wheat damage:

- Cylinder speed is the most significant factor influencing wheat damage on a conventional combine. Operators should be aware of the interaction of speed, clearance, threshing efficiency and grain damage, so that they can adjust to a reasonable compromise.

- Rotary combines produce significantly less grain damage than conventional machines, often reducing crackage by 2/3.
- Harvesting wheat at low moisture content aggravates crackage, but the effect can be minimized by lowering cylinder speeds when operating under such conditions.

Foreign Material and the Cleaning Process:

The cleaning shoe (item 6, figure 1-3) separates threshed wheat from chaff and other small plant parts that have passed through the cylinder concave or the bottom of the straw walkers. The shoe accomplishes this by a combination of air flow upward through the shoe and agitation of the material mat caused by the mechanical oscillation of the chaffer.

Downs et al. (1985) found that between 66% and 99% of the weed seeds produced were taken into the combine, and that 41% to 91% was delivered to the bin. This indicates rather inadequate performance of the cleaning shoe, in terms of eliminating cheat and other winter annual grasses from wheat. Downs examined machines as they had been adjusted by the operator, so the poor performance could have been due to either design inadequacies or misadjustments.

There are several avenues that have the potential to improve the effectiveness of cleaning mechanisms on current wheat combines, including:

a. Refitting current machines with the appropriate chaffers for wheat.

b. Replacing older combines with newer models having higher capacity cleaning systems with less slope sensitivity.

c. Incorporating secondary cleaners into future combine designs.

Refitting Existing Combines: Some U. S. wheat combines are improperly equipped for harvesting wheat. In general, conventional machines are built as "grain" and "corn/bean" configurations. The two types of machines differ in several areas. First, the concave of the corn/bean machine is equipped with wider gaps than the wheat machine, in order to allow the larger seed to pass through. The concave transition grate is usually a finger-type unit on corn machines and a cell type configuration on grain machines. Next, the straw walkers of the corn/bean machine are of a louvered bottom design, since the rectangular openings in the bottom of wheat straw walkers are prone to clogging by corn cobs. Finally, the chaffer sieve of the corn/bean combine has deeper teeth on the louvers and wider spacing between the louvers than does the wheat machine.

In parts of the country where wheat is grown along with corn or soybeans, corn/bean machines are often used for harvesting wheat. The extent to which performance is compromised by using a corn/bean machine on wheat is not well documented, but the expected impacts for a conventional combine would be a) lower separation capacity as a result of suboptimal cylinder, beater, and straw walker configuration, and b) poorer cleaning due to the wide spaced chaffer and larger quantity of material sent to the cleaning shoe by the corn concave.

Five types of chaffer sieves are available for U.S. combines, although all configurations may not be available for a specific model.

1. The standard grain chaffer with 1.125" louver spacings.
2. The 1.125" spacing "Peterson" chaffer.
3. "Airfoil" type non-adjustable chaffer.
4. The 1.625" spacing deep tooth corn chaffer.
5. The 1.625" spacing regular tooth chaffer.

The general consensus among the industry engineers contacted as a part of this study is that the first three types of chaffer sieves are preferred choices for wheat. The last two types, with 1.625" louver spacing, are difficult to adjust for small grains, and are expected to produce more foreign material at a given loss level. However, due to the wide variations in crop conditions, such recommendations are based on manufacturer's internal tests and observations, and no published test data are available comparing chaffer sieve styles.

The reduction in cleaning performance caused by operating with corn chaffer sieves can be corrected simply by changing to the proper chaffer while combining wheat. In fact, for years, one major U. S. combine manufacturer supplied a wheat chaffer in addition to the installed corn chaffer with all corn/bean combines sold. The cost of a second chaffer is $500-$800, and one man-hour of labor is generally ample time to make the substitution. Depending on the combine design, it may also be cost effective to change concaves or grates between crops.

Adopt Newer Technology: In recent years, numerous detail refinements have been made in the cleaning area of North American combines, although oscillating sieve cleaning remains the basis of most current designs. Conventional combines have gained capacity primarily from increases in separator width, although the length of the straw walkers and shoe have also been increased somewhat.

One problem created by the increases in width relates to the uniformity of air distribution across the cleaning shoe. Most combines use a paddle-type fan (figures 1-1, 1-3) to supply the air to the shoe. The air flows into such a fan through the ends of the fan, often leading to greater air flow velocities along the sides of the shoe. Some combine manufacturers have minimized such maldistribution by detail changes in fan blade design and air inlet shroud configuration. Stationary guide vanes may also be used to obtain a more uniform air distribution. Other manufacturers have adopted transverse flow fans (figure 1-4), which supply air to the fan along its entire length, creating more uniform air velocity across the shoe.

The use of air in the cleaning process has been investigated from several perspectives over the years. Uhl and Lamp (1966) concluded that chaff-like materials were separated from wheat at air velocities of 10 ft/sec less than that needed to suspend the wheat (19 to 30 ft/sec), implying that the difference in terminal velocities could be used to improve the separation and cleaning processes (figure 1-8). Others, including Hawk et al. (1966) used different experimental techniques, but arrived at the same general conclusions regarding the aerodynamic characteristics of wheat.

Several manufacturers have taken steps to increase the amount of pneumatic cleaning performed in the combine. In the early 1970's Massey Ferguson released its "cascade shoe," which allows the grain and chaff mat to free fall over three steps in the three section sieve, as opposed to only one free fall at the entrance of a conventional cleaning shoe. The cascade shoe was developed in response to very heavy chaff mats produced by Gaines wheat in the Pacific Northwest, irrigated wheat in the Southwest, and double-swath windrows in the Prairie Provinces. The heavy mats restricted the shoe airflow on conventional cleaning shoes, resulting in poor agitation and grain carry-over (Gordon et al., 1971). The three cascade gaps in the shoe tended to direct air flow through the freely falling mat, agitating the material and allowing the grain to penetrate the chaffer. At high feedrates,

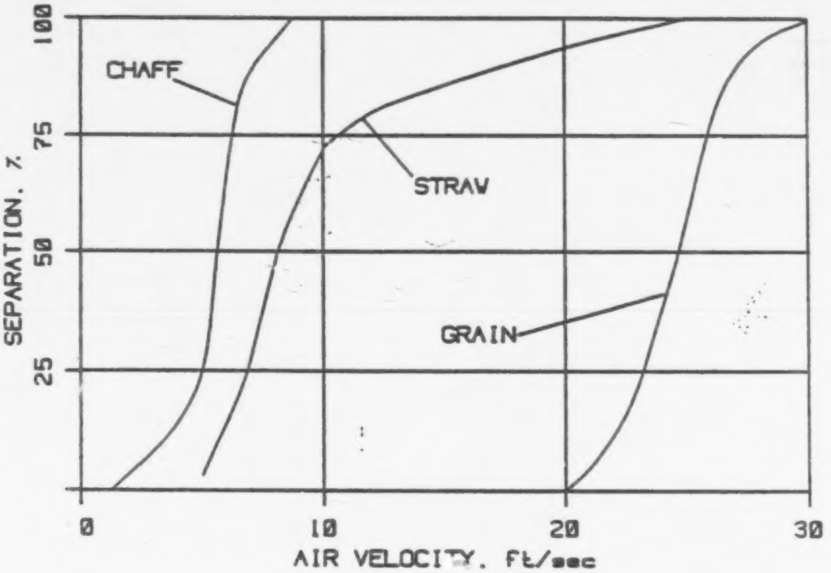

Figure 1-8. Separation of chaff, straw and wheat grain as a function of air velocity. From Uhl and Lamp (1966).

Gordon et al. reported more than a 90% reduction in grain loss for the 3 sieve cascade system.

For many years, "Gleaner" combines have pre-cleaned the grain and chaff prior to delivery onto the cleaning shoe (Quick and Buchele, 1978). Originally, two fans were used, with a "separator fan" supplying a rearward blast of air which was directed through the curtain of grain as it fell onto the cleaning shoe, while the second fan supplied the cleaning shoe in a more conventional fashion. The next development of two-stage cleaning occurred when a single transverse flow fan with two discharge ducts replaced the two separate fans. Since rotary combines often load the cleaning shoe more heavily than conventionals, the two-stage concept was further developed with the Gleaner rotary line, when "accelerator rolls" (item H, figure 1-4) were added to propel the grain downward through the rearward air blast from the upper fan discharge.

Sloping terrain affects cleaning shoe performance, whether the slopes be from side to side or front-rear. Simpson (1966) investigated the effect of front-rear slope on cleaning shoe performance, since not all hillside combines offer full front-rear leveling for the Pacific Northwest. Simpson's results indicated that losses were reduced but foreign material was increased as the angle of the cleaning shoe was decreased. The results are summarized in table 1-1. Since positive slope increases the rate of movement of material across the shoe, the increased loss and reduced foreign material are not unexpected consequences. Obviously, shoe adjustment when operating up and down slopes with a non-leveling combine is a compromise, with sub-optimal performance resulting in terms of loss and foreign material. Such problems can be eliminated by the use of a hillside combine with full leveling capability.

Side slopes are also detrimental to cleaning shoe performance, since the tendency is for material to congregate on the downhill side to the shoe, overloading that area and resulting in high grain losses. Several approaches have been developed to deal with this problem inexpensively. One relatively common approach is to equip the grain pan and cleaning shoe with vertical dividers to interrupt the movement of material to the downhill side. Another approach has been an attachment consisting of a blower and a pendulum-actuated valve to divert additional air flow to the downhill side of the shoe. The accelerator rolls used on Gleaner rotary combines also improve performance on side hills, since they propel the grain downward perpendicular to the cleaning shoe, thereby reducing the effects of gravity. Stahl et al. (1981) investigated an automatic control system which varied the halves of the cleaning fan independently. Resistor based anemometers were used to sense air flow on each side of the shoe and control air flow. The system produced a reduction in loss from approximately 9% to less than 1% when operating at high feedrates on a 12.3% side slope.

Table 1-1: Front-Rear Slope Effects on Cleaning Shoe Performance

Fan Opening %	Shoe Slope % (+ uphill)	Foreign Material %	Shoe Loss %
64	-10	2.37	0.22
64	0	1.32	0.44
64	+10	0.64	1.30
78	-10	0.85	0.60
78	0	0.49	0.17
78	+10	0.17	2.01

Source: Simpson, 1966

In 1974, John Deere introduced the SideHill 6600 combine, which was specifically designed to deal with moderate side slopes. The machine is hydraulically leveled in the roll mode, achieving performance close to that of a level combine on side slopes of 18%.

Secondary Cleaners: Some European combines offer secondary cleaning systems, sometimes in combination with a de-awner (The Green Book, 1984). The de-awner reportedly allows less vigorous settings of the main threshing cylinder and concave when harvesting moist, hard-to-thresh crops, and can be bypassed on some models of combines when it is not needed. Some secondary cleaners are rotary devices with interchangeable screens, and are intended to reduce the quantity of weed seeds in the grain delivered to the tank.

Secondary cleaners are retrofitted to some Australian combines, particularly those operating in areas that ship wheat directly to export elevators. The units are attached over the grain bin, and consist of a cylindrical screen rotating about its horizontal axis. Fine particles and small weed seeds that pass through the screen are bagged or conveyed to a second bin on the combine, while the wheat that does not pass through the rotating screen is marketed (Lukins, 1987).

Jiang et al. (1984) advanced the concept of an aerodynamic precleaner intended to reduce the load on the cleaning shoe. The precleaner would replace the combine's grain pan, and would convey the crop to the shoe in addition to precleaning it. The system consisted of an oscillating screen assisted by air flow directed rearward at approximately 40 degrees above the horizontal. The system removed 80% or more of the material-other-than-grain prior to delivery to the cleaning shoe, while maintaining low loss levels. While the system would require additional air flow, it has the potential for greatly reducing the cleaning load on a conventional shoe.

Outside Factors Affecting Harvesting Operations

Personnel

The combine is the most demanding machine to operate on most farms, both in terms of the operational workload and the knowledge required for adjustment and maintenance. A modern grain combine provides over 25 adjustments for tailoring the machine to specific conditions, and 7 to 10 of the most frequently changed adjustments are accessible from the operator's station. The combine operator must constantly monitor ground speed, cutting height, reel speed, and reel height as the machine moves through the field. In addition, crop conditions can demand readjustments within the the same field and within the same day.

The extent to which combine operators understand and appreciate the interactions between components and adjustments varies widely. Manufacturers have been active in increasing operator competence, primarily through the publication of operators' manuals, supplemental manuals, films, and computer software. State Extension Services have long conducted meetings on combine adjustment, loss measurement, and maintenance, and have made available publications and films on the same topics. With the inevitable turnover in operators, such ongoing educational activities are essential, and it may be appropriate to strengthen efforts on those subject matter areas that pertain to grain damage and foreign material.

Weed Control

Weed control is one of the most serious production problems facing winter wheat producers in the central great plains. Winter annual grassy weeds have become a major problem in those regions producing wheat on a continuous (year after year) basis, although they are a less serious problem in the fallow wheat regions. Winter annual grassy weeds that are particularly troublesome include downey brome (bromus tectorum), cheat (bromus secalinus, also called "chess"), Japanese brome (bromus japonicus), and jointed goatgrass (Aegilops cylindrica). Such weeds are costly both in terms of reduced wheat yield and increased foreign material in the wheat. The winter annual grassy weeds are difficult to control for several reasons:

1. Winter annual grassy weeds are genetically very similar to winter wheat, so there is a limited basis for chemical

selection. Those chemicals that have been labeled for the control of winter annual grassy weeds in wheat are often restricted to specific varieties that have demonstrated tolerance to the chemical during field trials. There is often a relatively narrow tolerance between rates of chemical which control the weeds and rates which damage the wheat.

2. The weeds' life cycle is very similar to winter wheat, which limits a producer's ability to control the weed with cultural practices. Producers sometimes delay wheat planting to allow the weeds to emerge so that they can be killed with chemicals or tillage. However, since the weeds emerge over a prolonged period in the fall, this practice has met with only limited success.

In the spring, the weeds mature, ripen, and begin to shatter prior to wheat harvest, insuring a supply of weed seed for the following crop season. Burning and/or moldboard plowing of the wheat stubble is often practiced in an effort to destroy weed seed viability or to preclude emergence of the weeds. Such practices, however, have environmental costs in the form of increased soil erosion resulting from a lack of surface residue cover.

At the present time, fallowing and crop rotation are the most effective methods of controlling winter annual grassy weeds in wheat. Fallowing (often in conjunction with the Acreage Reduction Program) removes the land from production for one crop cycle. Residue cover during the fallow season may be maintained by the chemical treatment of the wheat stubble or by the establishment of a cover crop. Rotation involves the production of a summer annual crop such as grain sorghum, soybeans, or corn for one or more years, followed by a return to wheat.

Fallowing and rotation enhance weed control by allowing the land to be treated with chemicals or tilled in the spring of the year. If such operations are performed prior to the time that the winter annual grassy weeds produce viable seed, the weed cycle can be broken. A substantial reduction of the winter annual grassy weed complex is possible in one year, but research indicates that two years of summer crops is often needed to achieve complete control (Ten Eyck, 1984).

Varieties

Trends in wheat kernel size are increasing the difficulty of removing winter annual grassy weed seeds from wheat. During the last 15 years, semi-dwarf varieties have become dominant in the central plains. One of the yield-enhancing traits of semi-dwarf wheats is the formation of more kernels per spikelet on the head, and the third through the fifth kernels are available for development if favorable late-season growing conditions exist. Frequently, however, the later kernels are not fully filled, resulting in a mixture of kernel sizes. The impact can be seen by comparing the kernel sizes of older and newer varieties. The first three varieties in table 1-2 are older, full height varieties, while the last three are more recent semi-dwarf varieties.

The average thousand kernel weight for the older varieties was 30.5 g, and an average of 55.2% of the sample was carried over a screen with 7 wires per inch. For the newer varieties, the averages are 27.3 g. and 46.8%, respectively. Both criteria indicate a trend toward smaller kernel sizes.

The trend toward smaller kernel sizes is of concern because, with the exception of jointed goatgrass, the seeds of most grassy weeds are smaller and lighter than wheat. Thus, smaller wheat kernel size reduces the margin between wheat and weed seed size and therefore increases the difficulty of cleaning within the combine shoe. The trend may not be important in all wheat producing areas, since thousand kernel weights in the pacific northwest are reported to range from 30 to 50 grams.

Government Programs

Current farm programs require that 25 to 30% of wheat base acreage be removed from production in order to qualify for program payments. The set-aside acreage creates one of the best opportunities for producers to control troublesome weeds, in that the fallow acres can be rotated to disrupt the weed life cycle with tillage or chemical treatment. This aspect of the programs can only be regarded as a positive influence on wheat quality.

Table 1-2: Varietal Effects on Wheat Kernel Size

	1975			1980			1985		
Variety	SS	TKW	OV 7w	SS	TKW	OV 7w	SS	TKW	OV 7w
Scout	88	36.9	56.6	25	27.7	50.9	10	28.9	50.0
Eagle	28	32.3	53.8	36	27.9	51.3	8	31.0	59.3
Triumph	6	28.5	51.6	17	31.0	67.2	-	-	-
Newton	-	-	-	36	26.7	45.0	77	25.9	43.8
TAM-105	-	-	-	-	-	-	36	30.6	45.3
Arkan	-	-	-	-	-	-	16	26.0	53.2

SS = sample size

TKW = thousand kernel weight, grams

OV 7w = % weight carried over 7 wire screen

Source: Kansas Wheat Quality, 1975, 1980, and 1985 Issues.

However, in those wheat producing areas in which grazing is common, there is a conflict between livestock income and weed control on the set-aside acres. If set-aside acres are grazed, producers often do not perform timely weed control operations during the spring of the fallow year, since to do so shortens the grazing period. If the cattle are allowed to graze after the wheat and grassy weeds produce viable seed, the weed control benefits normally associated with fallowing the land are not realized.

Financial Stress

The current depressed agricultural economy is magnified within the agricultural machinery industry. Major equipment items such as combines are among the first expenditures to be postponed by a producer encountering financial difficulty. Combine sales in the United States have shown major decreases during the 1980's, declining from 32246 in 1979 to 7660 in 1986 (Berzanski, 1987), a decline of 76% in 7 years. Current 1987 combine sales data are running behind 1986, showing no signs of a bottom.

To the extent that newer combine models are capable of producing less grain damage and cleaner grain than older (and possibly worn) units, the sagging market has been a negative influence on grain quality. The weak market has also slowed the development of new combine technology, due to cutbacks in research and engineering in most of the major manufacturers.

Strengths and Weaknesses

The high level of mechanization of the U. S. wheat harvest is a significant strength, particularly when compared with grain harvesting in developing countries. For example, in comparing wheat harvesting methods in Pakistan, Bukhari et al. (1983) placed the average grain losses on three farms using "conventional" manual harvesting methods at 16.07%, while a test combine produced a loss of 3.43%. Impurities were measured at 3.58% for the manual harvest and 2.03% for the combine.

Another strength of U. S. wheat harvest is the extensive use of "custom" wheat harvesting in the great plains. The biological "ripening front" of wheat that proceeds up the great plains creates the opportunity for machines to follow the harvest, a concept first exploited by the 500 combine "harvest brigade" during 1944 (Quick and Buchele, 1978). With custom machines concentrated where the crop is ripe, wheat harvest is completed rapidly, decreasing the crop's exposure to the elements. Also, since custom combines are operated for many more acres each year than the combines owned by individual wheat growers (Lagrone and Gavett, 1975), they are replaced more frequently and are therefore closer to the current state of the art in combine design.

One negative result of custom harvesting is a reduction in feedback to the producer. If a producer hires a custom cutter to harvest his crop, he loses the opportunity to observe the mature crop. Unless such a producer makes active efforts to scout the crop prior to harvest, he will be unaware of weed infestations or other problems that perpetuate themselves into the next crop if left unattended.

The large harvesting capacity of the current system also has negative implications, in that the large flow of grain into commercial channels tends to obscure the identity of grain. As a result, it is difficult to reward those producers who maintain high grain quality.

New and Emerging Technologies

Stripper Headers

A potentially significant development is occurring in the area of combine headers for wheat and other small grains. The British Technology Group has developed and licensed a new concept of stripper header. Stripper headers, as the name implies, remove the grain from the standing crop without cutting the stalk.

As currently developed, the Institute of Engineering Research (IER) stripper header employs a rotor that is equipped with plastic teeth which impact and strip grain from the wheat heads. The pointed teeth are formed from a strip of plastic with "keyholes" between the teeth to engage the head. The rotor turns at about 700 rpm, with the plastic teeth moving upward as they contact the plant. The grain is delivered over the top of the rotor to a conventional auger, which conveys the grain to the processing components of the combine.

The reported advantages of the stripper header include the low amount of material other than grain (MOG) that is delivered to the combine as well as the header's ability to operate at high speed. The MOG reduction allowed the combine's capacity to be increased by roughly 45% in U.K. tests on wheat (Hale, 1987), but header loss (at roughly 2% of yield) was higher than with conventional headers. Observations under U. S. conditions tend to confirm this performance.

The IER stripper header has great implications in terms of overall combine design. The lower MOG delivery should make possible lighter, more compact combines capable of traveling at higher ground speeds. While the stripper header loss appears high by current standards, many refinements remain to be investigated. The influence of the stripper header on grain quality is not known, but it appears that damage should be reduced, since the grain is threshed by contact with plastic teeth.

Control Systems and Automation

The commercialization of microelectronics has opened new possibilities in the control of combine operations. Currently, the main application of microelectronics is in the monitoring of combine parameters such as shaft speed and grain losses. A limited number of closed-loop control systems have been marketed, including automatic header height control and automatic reel speed control, but many concepts remain to be exploited.

Automatic control of combine speed (or feedrate) has been investigated as a means of increasing combine capacity (Schueller et al., 1982), and control of cylinder speed as a function grain moisture also shows potential (Mailander et al., 1982; Brizgis et al., 1978). Grain flow sensors and a means of mapping grain yield have also been proposed (Wagner and Schrock, 1986), and the cleaning shoe air flow controller of Stahl et al. (1981) is also significant.

One of the prerequisites to the development of a control system is the definition of a relationship between the parameter to be controlled and a measurable independent variable. Since the combine deals directly with biological materials, such relationships are often poorly defined and highly statistical in nature. In addition, sensors for measuring input variables are often not available. These problems, combined with the currently depressed state of the industry and the lack of a long term research effort, are likely to slow the development of closed loop control systems on combines.

Rotary Combines

Since they have been commercially available for some 12 years, rotary combines can hardly be classified as new. Most

U. S. combine manufacturers now offer rotary machines, but acceptance within the marketplace has not been rapid.

As manufacturers strive to reduce combine costs, the simplicity and lighter weight of the rotary designs may become more appealing. According to reports issued by the Prairie Agricultural Machinery Institute, conventional combines typically contain between 90 to 110 bearings. Rotary designs contain from 44 to 67 bearings, indicating fewer rotating parts, and implying a lower mechanical complexity.

Relationship of Grain Quality Attributes and Harvesting Machinery

The key grain quality attributes that are influenced by harvesting machinery are kernel damage and foreign material. It appears that moderate reductions in these negative attributes are compatible with current combine technology, the major challenge being to increase operator understanding of combine adjustments.

In the area of grain damage, improvements could be made by increasing the operators' awareness of the importance of moderate cylinder speeds. Other improvements will occur as the overall combine population gradually shifts toward rotary designs.

Although the prevalence of using corn-based combines in wheat is not known, it is likely that some reduction in foreign material is possible by ensuring that current machines are equipped with the appropriate chaffer sieves. Surprisingly little information is available comparing the performance of different chaffer designs, but the "Peterson" and "Airfoil" chaffers are being accepted in the marketplace. This tends to indicate that many operators have recognized the need for improvements in cleaning and are willing to evaluate new concepts.

Sanitation is influenced to an unknown (although probably minor) extent by combine design. Although combines are equipped with numerous doors to facilitate cleaning, thorough cleaning is an extremely difficult and unpleasant task. As a result, combines are usually stored with small quantities of grain remaining in the grain pan, various auger troughs, and numerous crevices. The situation creates a haven for rodents and insects during the machine storage period, and undoubtedly leads to some level of contamination of the first combine binful of grain at the start of a season. Greatest concern has been expressed by seed producers, who must clean machines when changing varieties to insure seed purity.

The emerging technologies discussed in this report all appear to be compatible with increased emphasis on grain quality. A common problem with the emerging technologies, however, is the currently depressed combine market, which discourages technical innovation by combine manufacturers and lengthens the time needed for innovations to influence grain quality.

The IER stripper header, since it decreases the MOG load on the cleaning shoe, facilitates the cleaning process and should therefore lead to reductions in foreign material. As currently designed, the stripper header would appear to reduce grain damage, but no test data are available to support this speculation.

The emerging control systems are in general neutral or positive with respect to their effect on grain quality. Some systems, such as automatic header height control, have little reason to influence quality attributes. Others, such as closed loop cylinder speed control, promise substantial reductions in grain damage.

Recommended Short and Long Term Changes

In the author's opinion, the performance of current harvesting machinery can be improved substantially by more careful operation and adjustment. An effective motivation for such increased awareness and attention is likely to be greater discrimination on the part of the grain buyer. Changes within the grain handling system which facilitate the equitable monetary compensation of individual growers based on wheat quality will encourage the production of high quality grain.

In the longer term, changes in combine design are likely to improve performance, particularly in the area of the cleaning system. Current combine cleaning system designs appear to be products of evolution, depending heavily on past experience and field testing programs. In many cases, component changes have originated with users and have been developed by the manufacturers to respond to customer demands. This approach has been made necessary by the highly variable physical properties of wheat as it is harvested in the field, and the lack of an organized research effort aimed at defining and measuring crop properties.

If the United States is to improve its competitive position with regard to grain quality, then all possible sources of damage and foreign material should be investigated. Given the weak condition of U. S. combine manufacturers, it is appropriate to strengthen public research efforts in harvesting and grain quality. Considering the wheat harvesting operation, the following efforts are suggested:

1. Characterize foreign material: What are the primary sources of foreign material in wheat delivered to market in various areas of the country? What are the physical properties of the foreign material, such as particle size distribution, density, and terminal velocity? Such information is needed to allow designers to develop combine alterations for removing such particles.
2. Determine physical properties of wheat: In the past, inadequate attention has been given to describing the statistical distributions of physical properties of wheat. For example, given the kernel size spread of current wheat varieties, what is a reasonable minimum kernel size that should be retained by the by the combine? Kernel size, density, and

terminal velocity information will assist designers with design improvements in cleaning systems.

3. Reevaluate fundamental harvesting procedures: Advances in materials and electronics may make yesterday's impractical concept a future reality. The IER stripper header, which uses plastic impact teeth to remove wheat from the heads of standing grain, is an example of a concept worthy of investigation.
4. Applied component evaluations: With regard to the combine cleaning system, today's combine operator has very little information on which to base purchasing and adjustment decisions. Commercially available cleaning components should be evaluated with regard to their ability to reduce regional foreign material problems.

Impact and Cost for Change

The costs associated with improving the adjustment of existing combines should be minimal. The largest cost would be a reduction in machine capacity, assuming more of the operator's time would be devoted to examining machine performance and making appropriate adjustments. In the author's opinion, a reasonable level of effort might be 30 minutes per day devoted to evaluating grain quality and making adjustments, or a reduction of machine capacity of about 5% if the combine is idled during the entire evaluation time.

Should equipment modifications be called for, the cost obviously depends on the nature of the changes. For example, a chaffer sieve for a large combine typically retails for $500-$800, while a set of rotary combine concaves generally costs $800 to $1400. If additional secondary cleaning devices become necessary to meet grain standards, the cost would likely fall in the range of $700 to $3000 per machine.

The costs of implementing the structural changes needed within the grain trade to encourage higher wheat quality are difficult to assess, and are best estimated by knowledgeable professionals in the area of grain marketing.

The manpower needed to conduct the harvesting-related research suggested in the previous section depends on the speed at which results are desired. However, given the seasonally variable nature of crop properties, a minimum of three years' data is needed to produce reliable results. The author estimates that a total of 12 full time researchers with appropriate support staff would be required to make meaningful progress toward the objectives in that length of time.

Summary

Self-propelled combines are used to harvest nearly all of the wheat produced in the United States, as well as most other grain crops. Current combines are of either "conventional" or "rotary" design, the latter type of machine being introduced during the 1970's by several manufacturers. Both designs are well adapted to U. S. conditions, although the demands for multiple crop capability have made certain design compromises necessary.

The two grain quality attributes most influenced by the combine are kernel damage and foreign material. High threshing cylinder speed is the predominant cause of grain damage, although grain handling augers on the combine can also contribute to the problem. The available literature comparing grain damage on wheat (Fairbanks et al., 1978) suggests that rotary combines produce significantly lower levels of grain damage than do conventional combines.

The combine component having greatest influence on foreign material is the cleaning shoe. All combines use a set of reciprocating sieves, assisted by upward airflow, as the primary cleaning device. Some manufacturers have enhanced the shoe by pre-cleaning the grain prior to delivery onto the shoe. In all cases, different chaffer sieves are available for corn and soybeans as opposed to wheat, and use of a corn chaffer while harvesting wheat increases the difficulty of removing foreign material. The number of wheat producers who operate their combines with corn chaffers is unknown, but it is believed to be significant in some geographic regions.

Improving the performance of current combines is largely a matter of increasing operator awareness of the importance of combine adjustments. Adequate threshing can be obtained with moderate cylinder speeds which will reduce grain damage to acceptable levels. Refitting a corn combine with a wheat chaffer sieve is a minor task, but many operators are unaware of the need to do so.

Stripper headers represent a particularly interesting emerging technology. Under prototype development in the United Kingdom, stripper headers dislodge the grain from the wheat head without cutting the stalk, using a rotor equipped with plastic teeth to impact the head. The header discharges a mixture of grain, chaff, and head fragments, which at this stage of development is fed to a conventional combine. Much less material-other-than-grain is fed into the combine than with a conventional header, allowing substantially greater combine capacity. The influence of the header on grain quality is not yet documented, but preliminary observations indicate the potential for reductions in both grain damage and foreign material.

Other emerging technologies include automatic control systems for cylinder speed, combine travel speed, and other combine functions. Controlling cylinder speed as a function of grain moisture appears promising with regard to reduced grain damage, and most other control systems under development will have neutral or positive impacts on grain quality.

Several recommendations are given for improving the near term performance of existing harvesting equipment. First, structural changes in the grain handling system should facilitate the equitable compensation of producers based on grain quality. Educational programs to increase operator understanding of combine component selection and adjustment should be strengthened.

In the longer term, research is needed to characterize the physical properties of wheat and foreign material on a statistical basis. Performance data comparing available combine cleaning equipment is currently unavailable, and new harvesting and cleaning concepts originating in other countries should be evaluated under U. S. conditions.

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Background Paper No. 3

Handling and Storage of Wheat: An Assessment of Current Technology

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HANDLING AND STORAGE OF WHEAT: AN ASSESSMENT OF CURRENT TECHNOLOGY

D.B. Sauer and H.H. Converse

This report covers the equipment, facilities and procedures used in the handling and storage of wheat from the time it leaves the combine until it is loaded in a truck, rail car or vessel en route to its end user. It does not include the transporting of grain from one location to another. Grain handling and storage systems have developed over the years to provide an economical means of moving grain into storage, preserving its quality while in storage, and moving it within or unloading it from the storage facility. Speed and ease of loading and unloading are issues of prime concern. It is generally assumed that storage and handling do not improve the quality of grain; rather, they either decrease or maintain quality.

CURRENT WHEAT STORAGE TECHNOLOGY:

Total grain storage capacity in the U.S. is about 23 billion bushels, of which 14 billion is on-farm and 9 billion is off-farm storage. The proportion of wheat stored on farms is lower than for other grains. Typical grain stock reports will show about one third of the wheat in farm storage. Table 1 lists the amount of wheat on and off farms in the U.S. since 1975. Table 2 shows wheat stored in some of the principal wheat states as of September 1, 1987 and the total grain storage capacity in those states. Major wheat producing areas in the southern plains tend to have most wheat stored in commercial facilities, whereas northern states have a higher percentage stored on farms. Kansas

Table 1. U.S. wheat stocks since 1976, in millions of bushels.

Date	On farms	Off farms	Total
Sep 1, 1987	1145	1813	2958
Jun 1, 1987	560	1261	1821
Sep 1, 1986	1293	1862	3155
Jun 1, 1986	681	1224	1905
Jun 1, 1985	582	843	1425
Jun 1, 1984	592	807	1399
Jun 1, 1983	669	846	1515
Jun 1, 1982	576	583	1159
Jun 1, 1981	414	575	989
Jun 1, 1980	377	525	902
Jun 1, 1979	484	440	924
Jun 1, 1978	494	684	1178
Jun 1, 1977	527	686	1213
Jun 1, 1976	236	430	666

Table 2. Wheat stocks stored in principal states on September 1, 1987; total grain storage capacity as of December 1, 1986; and wheat stocks as a percentage of storage capacity.

	Wheat Stocks			Storage Capacity			Stocks as % of capacity		
State	On-farm	Off-farm	Total	On-farm	Off-farm	Total	on-farm	off-farm	Total
	--------- Millions of bushels ----------								
Calif	5	26	31		108			24	
Colo	65	58	123	264	131	395	25	44	31
Idaho	56	58	114	184	107	291	30	54	39
Ill	7	28	35	1322	1149	2471	1	2	1
Ind	4	23	26	759	358	1117	1	6	2
Kans	82	424	506	474	913	1387	17	46	36
Mich	4	17	21	296	135	431	1	13	5
Minn	145	95	240	1460	555	2015	10	17	12
Mo	8	30	38	433	279	712	2	11	5
Mont	167	45	212	369	57	426	45	79	50
Nebr	55	93	148	1288	813	2101	4	11	7
N Dak	290	113	403	901	229	1130	32	49	36
Ohio	5	42	49	436	318	754	1	13	6
Okla	26	140	166	131	262	393	20	53	42
Oreg	26	53	79	81	82	163	32	65	48
S Dak	105	38	143	604	118	722	17	32	20
Texas	7	224	231	230	869	1098	3	26	21
Wash	41	168	209		239			70	
Total	1145	1813	2958	13830	9127	22957	8	20	13

and Montana illustrate this contrast. The states which are primarily corn and soybean producers stand out in Table 2 in that their wheat stocks represent a small part of their grain storage capacity.

A recent survey of on-farm wheat storage in Kansas showed more nonaerated than aerated bins, but the aerated structures averaged more than twice as large and accounted for about 60% of the total storage capacity (Reed, 1986). Commercial wheat storages are nearly all equipped for aeration, especially the horizontal or flat storages. In some states, warehouse licensing regulations require that all such storage space be aerated.

Sources of information on grain storage facilities and their design and operation include brochures from manufacturers and contractors, structural engineering texts, review articles (Bailey, 1982), government reports (Graves, 1964), and publications of industry associations (Gordon, 1985). A wide variety of sizes and types of structures are illustrated and described in such publications.

An on-farm storage and handling system should be designed to maintain the harvested grain quality from the time it comes from the field until it is delivered to the elevator or mill. Wheat storage structures should meet the following criteria: They should be a structurally sound design, such as corrugated steel bins, bolted steel tanks, or flat storage buildings. The walls and foundations should be strong enough to withstand the pressure exerted by grain, and the bins should be able to withstand wind, hail, snow and other weather conditions. They should be as gastight as possible to enable fumigation of the entire stock in storage. They should be equipped with a controllable ventilation or aeration system so as to minimize temperature variations within the grain bulk, and to keep the grain cool. The bins should be free of ledges or cracks where dust and grain residues may lodge and provide harborage for pests. They should by constructed so as to prevent the entry of birds and rodents. In actual practice, farm storages range from old wooden sheds and granaries to various sizes of flat storages and circular steel bins. Older wooden bins have for the most part been replaced with metal bins.

The layout of a storage and handling system should be designed for efficient loading in and out and for any drying or cleaning that might be necessary. Many farm grain storages do not have an efficient storage and handling design, because it may not be critical to the farm operation. An inefficent system on the farm may mean extra handling and labor, but will not threaten to put the owner out of business.

Commercial grain handlers must give considerable importance to the design and operation of their facility. To be competitive they must be able to offer low-cost services to the customer in a timely manner. Considerable attention must be paid to factors like location, utilities, transportation access, traffic flow, loading and unloading capacities, size and efficiency of conditioning equipment, and of course keep overall capital and operating costs at a minimum. Overall annual costs per bushel of grain handled decrease as elevator size and volume increase (Schnake, 1983).

Deterioration or quality loss in storage is cumulative and generally increases with increasing storage time, but should not be looked upon as inevitable. There are many examples of wheat and other grains being stored for several years without significant loss. One report covered changes that occurred in dry wheat during 16 years of storage (Pixton, 1975). The authors reported no mold growth and no changes in odor or appearance during that time. Viability of the wheat gradually declined at room temperature, but remained at 96% when stored at 4-5 C. Free fatty acids increased during storage, the increase being half as fast at the lower temperature. The wheats yielded satisfactory bread throughout the storage period although a deficiency of alpha amylase became apparent after 8 years and required supplementation.

Aeration

Maintaining low temperature and moisture levels in grain are the principal ways to preserve its quality and prevent damage from insects and molds (Converse, 1977; Foster, 1982). Aeration is a very effective and economical management tool for temperature and moisture control. The rate of development for both insects and molds is greatly reduced as temperature is lowered. Tests in a wide variety of climates has shown very good insect control by using aeration (Bloome, 1984; Ghaly, 1984; Halderson, 1985). Insecticidal protectants may not be needed if aeration is used effectively. A properly designed and operated aeration system will remove the heat from freshly harvested wheat and will maintain relatively low and uniform temperatures throughout storage. Uniformity of temperature is important because temperature gradients cause moisture to transfer from the warm to the cool areas. When moisture increases to about 14% or more, fungi or molds will grow in the grain (Christensen, 1969; Christensen and Sauer, 1982; Tuite, 1979).

Aeration systems generally will provide an airflow rate of 0.02 to 0.1 cfm per bushel of grain. This is equivalent to 2 to 12 changes of air per hour. Aeration fans are usually located at the base of a bin wall and can be operated so as to create a positive pressure pushing air up through the grain or a negative pressure pulling air down through the grain. Some installations have fans mounted in the roof or top of the bin and some use fans top and bottom, pulling and pushing the air.

Resistance to airflow increases with grain depth so more power is required to aerate deep silo-type bins compared to shallow or flat storages (Kline, 1961). As a rough guide, 1 kw of power is needed per 10,000 bushels for aeration of deep concrete elevator bins, but the same power is adequate for about 30,000 bushels of flat storage. Aerated bins or warehouses must have adequate ventilator area in the top to allow air to enter or leave when the fans are running. The vent openings should have an area four times the outlet area of the aeration fans.

There are some advantages and disadvantages to positive pressure and negative pressure aeration systems. Advantages of a positive pressure upward airflow: The heat from the fan and motor raises the air temperature and lowers relative humidity, thus permitting aeration during times when ambient air is a little too cold or too humid. There is a small increase in fan efficiency and air volume, and better airflow distribution along perforated ducts compared to negative pressure systems. This is important for long ventilating ducts used in flat storages. Warm grain can be added to the top of a bin partly filled with cool grain without pulling the heat from the warm grain though the previously cooled grain. Similarly, upward airflow is preferred when adding new grain with high moisture content to a bin, so that moisture removed will not be added to grain already dry. A disadvantage of upward airflow is that moisture often condenses on bin roofs and exposed walls when warm grain is aerated during cold weather. The condensed water may drip or run down the walls and wet the grain.

Advantages of negative pressure downward airflow: Warm air coming from grain being cooled is expelled from the bin through the aeration duct and fan at high enough velocities to prevent moisture condensation. Air pulled into the grain at the top of the bin is less likely to carry dust and debris into the grain or the aeration system. The progress of grain cooling can be easily monitored in the airstream being exhausted by the fan, since the bottom of the bin will be the last grain to cool. Odors coming from the fan can give an early warning of insect or mold problems in the grain. Disadvantages are that fan energy as heat can not be used to lower the humidity of incoming air when drying would be desirable, and that solar heat gain through the roof may reduce relative humidity and dry the grain when drying is not desirable.

Dewpoint temperatures are a good guide to estimating the minimum temperature to which grain can be cooled by aeration. Weather records for the time of year and geographic area in question can be consulted for such information. For example, dewpoint temperatures in midsummer are several degrees lower on the high plains of western Kansas, Oklahoma and Nebraska compared to the eastern portions of those states. Such a temperature difference can make insect control by aeration more effective in the cooler areas.

Aeration is used primarily for temperature control, but grain moisture may be changed depending on humidity, airflow rate and length of aeration time (Foster, 1967). Wheat is a hygroscopic material and will equilibrate with the air to which it is exposed. At 70 F wheat will equilibrate to approximately the following moisture contents at the selected relative humidities (RH): 11.4% at 50% RH, 12.7% at 60% RH, and 14.3% at 70% RH. At any given RH the equilibrium moisture will be lower at higher temperatures and higher at lower temperatures. If wheat with 13% moisture is aerated with air at 40% RH there will be a gradual moisture loss from the grain. Humidities above 70% would tend to add moisture to the grain. In a grain mass that is not being aerated, the air in the intergranular spaces will quickly equilibrate to the relative humidity that corresponds to the moisture and temperature of the grain.

Condensation in aeration ducts can be a problem when the fans are not running during warm weather when the grain mass is cold. If outside air can enter the duct, which would be cold, moisture would condense in the duct. Likewise, moisture from a warm grain pile can condense on a cold aeration duct exposed to outdoor air. The moisture accumulation will allow mold to grow, sometimes caking the grain around the perforated ducts. Therefore, air valves or tight-fitting covers should be used to prevent air infiltration during times when the fans are not running.

Agricultural extension specialists who deal with grain storage management report that many bins, especially at the farm level, are equipped with aeration systems, but they are often not used effectively (Harein, 1985). The most common problem is not running fans long enough to bring the entire grain mass to a uniform temperature level. If a cooling front is moved through only part of the grain, there is likely to be a moisture condensation problem at the point where warm and cold grain meet. A 1980 survey of farm-stored wheat indicated that aeration was not used very much in the north central states, where it could be used quite effectively for preventing insect and mold population buildups (Storey, 1984)

The marketing system rewards a seller for providing grain with the maximum allowable moisture. Discounts are assessed if moisture is above a certain level, but premiums are not paid for grain with lower moisture. Because aeration tends to remove moisture from grain, it removes weight that could be sold as grain. Below the moisture discount level a pound of water has the same value as a pound of wheat. For that reason many grain storage managers avoid running aeration fans more than the minimum considered to be necessary. This is a particularly serious problem in the southern plains area where harvest moistures are often very low. Rather than keeping moisture low for optimum storability, farmers and others have sought ways to add water to their dry wheat in order to increase their income when they sell the grain (Bloome, 1982).

Nonaerated Storage

As mentioned above, most commercial wheat storages are equipped with aeration. Farm storage bins, especially smaller and older bins often are not aerated. Small bins, less than 3000 bu, will cool or warm quickly enough with the changing seasons that moisture condensation may not be a serious problem. With larger grain masses, moisture migration from warm to cool portions of the bin becomes more of a certainty. The most common situation of this type is when wheat which still retains most of its summer heat is exposed to cold winter temperatures. Even though the grain may contain only 11-12% moisture, the convection currents up through the warm grain mass to the cold surface will result in condensation at that point. The surface grain may exceed 30% moisture content and will sprout and become caked with mold.

There has been an interest recently in storing grain in completely sealed structures without aeration. Such storages have been used in various parts of the world for many years, for both dry and damp grain (Hyde, 1982). Sealed bunkers have been used fairly extensively for several years in Australia to store dry wheat. Sealed bins or bunkers have the advantage of being easy to fumigate if insect infestations occur, but there are also claims that insects cannot live in sealed grain because the normal grain respiration uses up the oxygen and produces carbon dioxide, thus creating an atmosphere in which insects cannot survive. This approach has attracted recent attention because of the increasingly limited chemical controls available to deal with insects. Fumigation or purging of airtight structures with inert gases is another option to chemical fumigants (Shejbal, 1973). The limited amount of practical experience with sealed storage suggests that it is not possible to create and maintain an inert atmosphere in dry grain by natural means. Also, the problems of moisture migration will be the same as in any other nonaerated structure of similar size.

Transfer Turning

Turning is the process of physically moving grain from one storage bin to another. It is used primarily in upright storage facilities which have conveying equipment for unloading bins and for transferring the grain to another storage bin. Commercial elevator operators have long followed the practice of turning grain for purposes such as blending, sampling, fumigating, and mixing grain from the bin perimeter with grain from the center of the bin. The turning and transfer mixing contribute to a more uniform moisture content and temperature to control moisture migration. In upright storages not equipped with temperature monitoring cables and not accessible for sampling, turning the grain may be the only way to inspect the grain for insect infestation, heating, and moisture accumulations. Grain turning and blending are also management and marketing tools used to obtain uniform lots with respect to any desired quality factor such as protein content, moisture, or grade. Grain from two or more bins can be blended for shipment or for storage as a segregated lot with known characteristics.

When hot spots are detected, the affected bin may be transfer turned to break up the hot spots and to allow the manager to identify and treat the cause. In facilities not equipped with aeration, turning has been a traditional means of grain cooling. However, turning requires much more energy than does aeration in accomplishing that purpose, and the physical handling of the grain contributes to grain breakage and generates dust. When the storage facility has a continuous flow grain dryer, warm or damp wheat can be moved from one storage bin to another through the dryer with the dryer fan blowing ambient air through the grain. This will result in a greater reduction in temperature or moisture than would be accomplished by normal turning.

Refrigeration

Maintaining low temperatures in storage is desirable from the standpoint of quality preservation. Using mechanical refrigeration rather than ambient aeration has been attempted in several countries including Australia (Hunter, 1980), Israel (Donahaye, 1974), and England (Burrell, 1967). A large refrigerated dome storage system was marketed in the 1960's in the U.S. for corn, but without success. These experiences have shown that it is possible to cool large grain bulks even in warm weather, but the equipment and operating costs are such that they have not been competitive with alternative grain management options.

Refrigerated storage may be economically feasible in areas where summer temperatures are not low enough to provide adequate insect control with aeration, and where chemical controls are not an option. Further restrictions on grain protectants and fumigants might make refrigeration more appealing. Burrell (1982) reviewed the literature on grain chilling and noted that in spite of some reported successful applications, it has had little worldwide impact.

Temperature monitoring

Temperature monitoring in grain is usually accomplished by hanging temperature cables from the roof or top of a bin, and extending down through the grain bulk. Each cable consists of a steel support cable and a number of copper-constantan thermocouple wires, all in a protective plastic sheath. Cables can be placed in a bin before it is filled or they can be probed into the grain, as in flat storages or piles. The spacing of thermocouples and the spacing of cables depends on the size of the storage and the extent of monitoring that is desired or that can be justified. Grain that is heating more than one or two meters from a thermocouple may not be detected until considerable damage is done in the hot spot.

Thermocouples may be read by manually plugging each cable connector into a readout device or they may be wired directly to a central office or location where they are periodically read or automatically recorded at preset intervals. Temperature increases that cannot be explained by changes in ambient conditions are a signal of possible insect or mold problems which should be investigated by sampling and inspection. Commercial warehouses have relied on temperature monitoring systems for years to prevent serious spoilage, and many farmers also monitor grain temperatures. Small bins can be monitored by probing a protected thermometer into the grain at various locations, allowing the temperature to stabilize, and withdrawing and reading the thermometer. An even simpler but effective system involves pushing a steel pipe into the grain for a few moments and feeling the warmth or coolness of the metal as the pipe is withdrawn.

Most temperature monitoring in commercial facilities is done on a fixed schedule, either manually or by automatic recording equipment. A few elevators have installed programmable temperature monitoring equipment which can be used in conjunction with aeration fan controllers. Such a system can be programmed to respond to an increase in grain temperature by switching on an aeration fan. It may also be possible to limit fan operation to a predetermined band of ambient temperatures and humidities. The cost of such programmable monitoring and control systems has limited their use to a few large companies that can afford them.

WHEAT HANDLING

In this section are described the various kinds of equipment used to move grain horizontally or vertically within a farm or commercial storage facility. The advantages and disadvantages of each system for various applications are discussed. Illustrations and descriptions of handling equipment used in commercial facilities can be found in Gordon (1985). The grain quality concerns with regard to handling operations are the breakage and abrasion that may result. Several studies have been done on the comparison of different kinds of grain, equipment and other factors that affect mechanical damage in handling (Foster, 1973; McKenzie, 1985)

The belt bucket elevator, commonly called an elevator leg or leg, is the primary means of vertical movement of grain in commercial grain handling and storage facilities. It consists of an endless belt to which are attached evenly spaced buckets. The buckets are filled by scooping

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up grain at the bottom or boot of the leg; grain is discharged at the top of the leg by centrifugal force as the buckets pass over the head pulley. After discharge, the grain flows by gravity through spouting or can be moved horizontally by belts or other conveying devices.

The up side of the leg has a straight vertical casing; the down side may be straight for small capacity elevators,but large capacity legs with head pulleys larger than 36 inches usually have an offset casing design with a bend pulley above the boot section. The offset leg has a boot pulley smaller than the head pulley. There are several kinds of boot designs, all of which serve to tighten the belt and to some extent to align it so it does not rub on the casing or boot housing. The main design and operational concerns with bucket elevators include the following: location of the leg, running clearances inside the casing, inspection and service openings, service access, type and location of bearings, sensing and monitoring systems, belt take-up, type of buckets, belting fabric and its static conductivity, routine inspection of moving parts, and proper operating procedures.

Commercially built bucket elevators are available in any size and capacity to meet the vertical lift requirements of both large and small elevators and mills. Energy use and general operating costs are less for bucket elevators than for other vertical lift devices, so they are the system of choice in most commercial grain handling facilities. A system using a bucket elevator for most conveying often is the most expensive initially but its efficiency for high volume use offsets the capital cost disadvantage. Bucket elevators are available in heights and capacities to suit the needs of high volume grain handling and storage facilities on farms, but their initial costs and their fixed location make them an unlikely choice for most farm operations. They are best adapted to use in a well planned, permanent grain handling facility.

Bucket elevators each have a designed capacity according to height, bucket size, and motor size. However, they operate relatively economically at less than their rated capacity, unlike some other grain handling devices. Also, there is no problem with increased grain damage when they are operated at partial capacity. The amount of grain damage that occurs in bucket elevators is affected by the type and size of buckets, the belt velocity and transfer loading of the buckets. Overloading of buckets causes spillage or back-legging in the casing and can increase kernel damage. Belt velocities of 2.5 to 3.0 m/s (500 to 600 feet per min) are adequate for most leg designs and will minimize impact damage.

Loading grain on the up side of a leg causes more damage than loading on the down side (Foster, 1973), and this is a design consideration for elevators handling corn. For wheat, however, there does not appear to be a detectable difference when the leg is operated at normal speeds. Some small systems used on farms, however, move at higher speeds and may cause some physical damage if loaded on the up side.

Belt conveyors are the primary means of moving grain horizontally in most commercial storage and handling facilities. They consist of a flexible endless belt supported by rollers and driven by a shaft-mounted speed reducer and motor. They are usually open, but may be covered when used outside of a building. The belts vary in width up to 2 meters and are operated at speeds up to 500 or 550 feet per minute. They can be inclined up to 15 degrees, but should be nearly horizontal at the point of loading. The design of belt conveyors has become a sophisticated science, especially with regard to inclined and downhill conveyors.

Belt conveyors can accommodate a wide range of speed or volume demands in grain handling facilities. They are energy efficient and have relatively low maintenance and operating costs. Mechanical damage to grain is minimal when moved with belt conveyors. Most are used in fixed installations, but portable inclined models are available for use in loading flat storages and piles.

Drag flight conveyors are enclosed tubes in which moves a chain with attached paddles or flights. The chain is driven by a shaft and sprocket in the head discharge section with an idler shaft and sprocket in the tail section to maintain tension on the chain. As the flighting moves, it carries grain with it. Two different designs and conveying characteristics are available, the U-trough paddle flight conveyor with an oval bottom and the bar flight flat bottom (en masse flow) conveyor. The flighting is closely spaced in an en masse conveyor and when the conveyor is filled to capacity, the grain moves as a bulk mass. An en masse conveyor can move grain both horizontally and vertically.

Drag flight and en masse conveyors are available in a wide range of sizes and capacities, as fixed location or portable models. They are relatively inexpensive to buy, are easy to load, move grain at low velocities (about 1 m/s or less), and require less space than other equipment such as belt conveyors. However, they have higher motor power requirements than belt conveyors and because of their enclosed design are subject to insect infestation problems. The demand for low-cost conveyors has resulted in a great increase in the use of drag conveyors and in design changes to meet customer needs.

Screw auger conveyors have for many years been the principal means of moving grain on farms or wherever inexpensive portable equipment is needed. They consist of a round tube with a continuous spiral or screw inside, and can be powered by farm tractors or with electric motors. They are space efficient, portable, and can move grain horizontally or at relatively steep angles. On the negative side, they have high power requirements and can cause considerable grain damage, depending on the design and operation of the auger.

Pneumatic conveying is a system that moves bulk grain by air inside a pipe. The air-moving device must be able to provide the air velocity and sufficient pressure to overcome the airflow resistance and the resistance of the grain to flow through the system at the desired rate. Wheat conveying systems use an air velocity ranging from 31 m/s (6000 ft/min) without grain to 15-16 m/s with a load. Normal operating velocities are between these extremes. Pneumatic systems may be classified into three categories according to operating pressure and the kind of air-moving device.

High pressure systems operate at 10 to 15 pounds per square inch (psi) with relatively low air volumes provided by positive displacement air pumps. They are generally used for materials like feed or flour rather than whole grain. Medium pressure, 2 to 5 psi, systems use high air volumes from air turbines or multi-stage blowers. Low pressure systems operate at 1 to 2 psi at high volumes from centrifugal blowers. The medium and low pressure systems are the most suitable for grain conveying, particularly at high flow rates. They can also be used for conveying in flour and feed mills and for dust control systems. Both portable systems and fixed installations are available.

The portable combination systems use both positive and negative pressure to move grain. They use a negative pressure or suction side to draw air and grain into a cyclone-type separator where the grain falls out and the air moves into the inlet side of the blower. The positive pressure from the blower is forced through an air-lock feeder which loads the grain into the conveyor pipe. Air and grain are blown out the discharge end of the conveyor pipe. The combination systems have versatility and convenience not available in other mechanical grain conveying systems.

Portable pnuematic conveyors often are used to pick up grain that has been piled on the ground or in temporary storage structures. There may be more of a tendency to pick up every last kernel with such a device, which means any spoiled grain and quite a bit of dirt also get picked up.

The capacity of a pneumatic system is a function of conveyor size, power supplied, and the vertical and horizontal conveying distance. Pneumatic conveying normally requires more power than bucket elevators, belt conveyors and en masse drag conveyors. Most conveying systems have crevices or spots where fines accumulate and cause sanitation and insect infestation problems. Pneumatic systems are inherently cleaner since they do not have moving chains, belts or shafts inside the conveying tube and the tube is swept clean by the air moving through it. Pneumatic systems are more convenient and versatile for some applications, they are space efficient, can increase handling capacity, and are well adapted to the trend toward automation in bulk handling.

Factors that increase kernel damage in pneumatic systems include air velocities above 31 m/s with light grain loading, poor mechanical pipe joint connections and overloading of air-lock feeders. As with other handling equipment, however, mechanical damage in wheat is not a big concern like it is in corn. The major reason pneumatic systems are not used more widely in commercial grain handling systems is the high energy input and power cost.

The typical monolithic slipformed concrete grain elevator structure is ideally suited to the efficient handling of wheat. Such a structure makes optimum use of gravity spouting, all-steel bucket elevator leg casings, electrically operated grain samplers, and electronic control of conveyor, loading, and grain-flow valves. The country elevator bin plan illustrated in Figure 1 has a sidewall height of 136 feet; a headhouse above the bins contains the weighing, cleaning, and distribution operations for the facility. The grain flow schematic in Figure 2 illustrates the equipment and the pathways used to handle grain in the elevator. A river terminal elevator with facilities for receiving grain by truck and rail and for loading out mainly by rail and barge is shown in Figure 3.

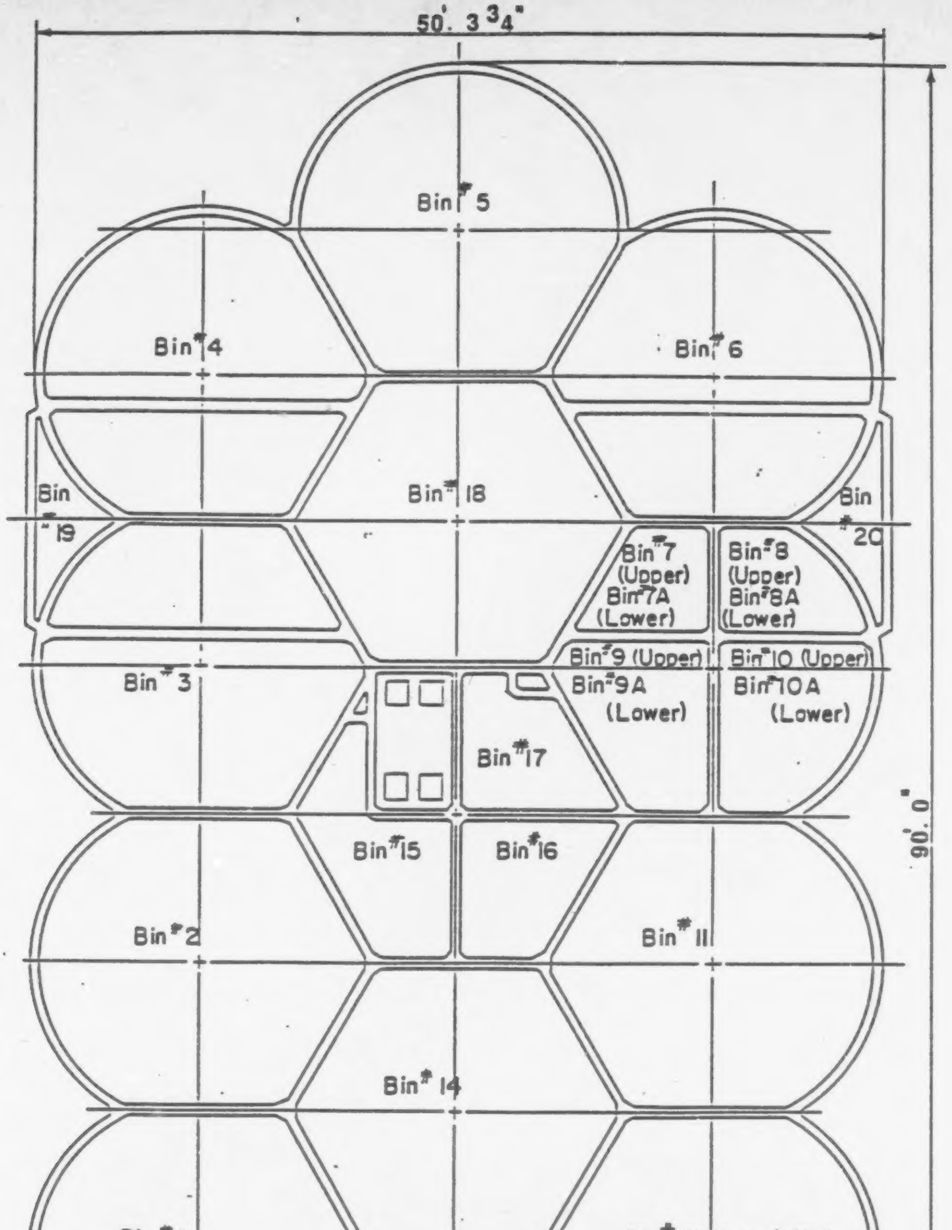

50' 3 3/4"
90' 0"
Bin # 5
Bin # 4
Bin # 6
Bin # 19
Bin # 18
Bin # 20
Bin # 7 (Upper) Bin # 7A (Lower)
Bin # 8 (Upper) Bin # 8A (Lower)
Bin # 9 (Upper) Bin # 9A (Lower)
Bin # 10 (Upper) Bin # 10A (Lower)
Bin # 3
Bin # 17
Bin # 15
Bin # 16
Bin # 2
Bin # 11
Bin # 14
Bin # 1
Bin # 12 (Upper) Wet
Bin # 12A (Lower) Dry
Bin # 13

Figure 1. Drawform bin plan of a gravity design country grain elevator, 350,000 bushels of storage capacity.

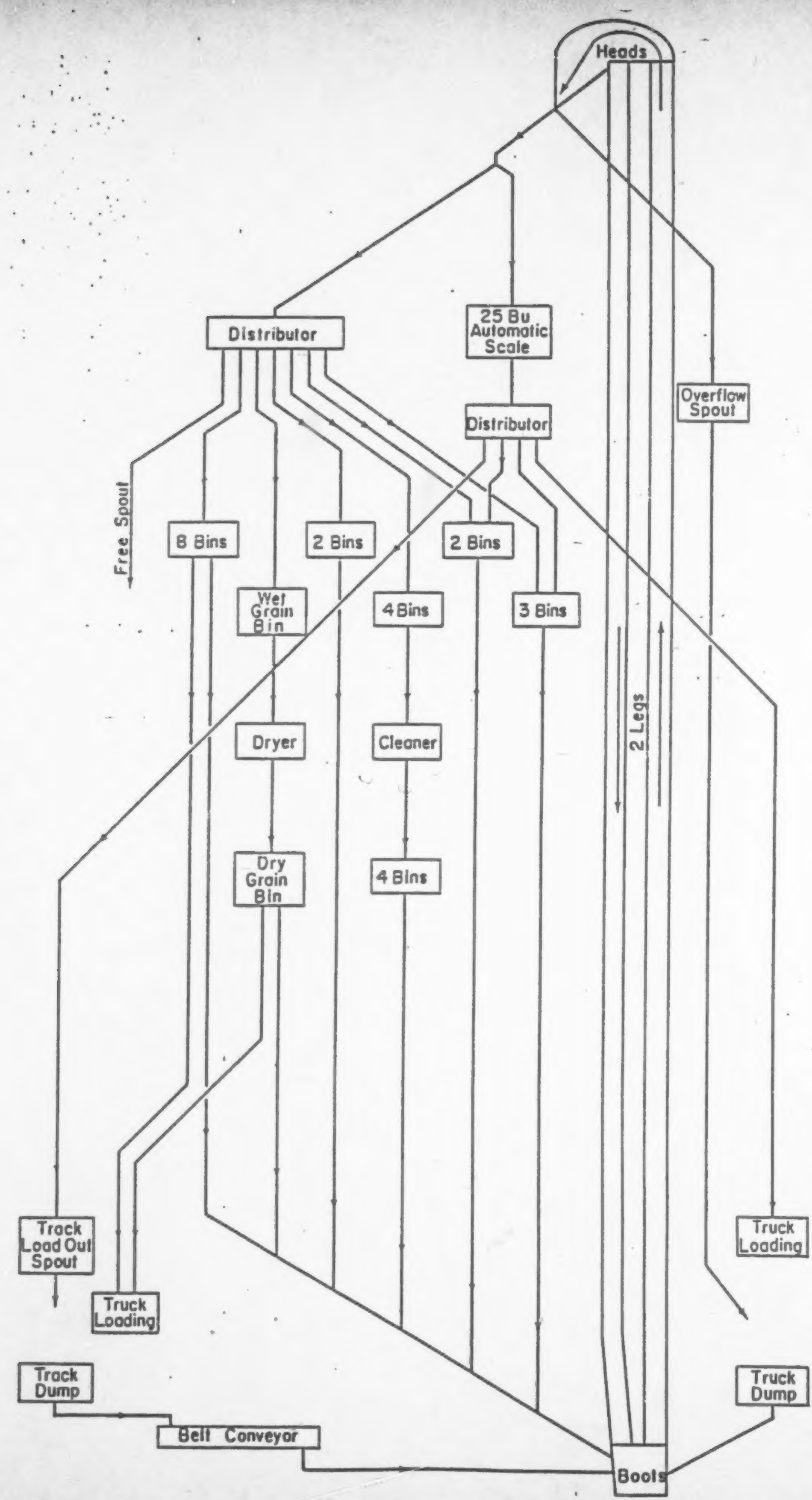
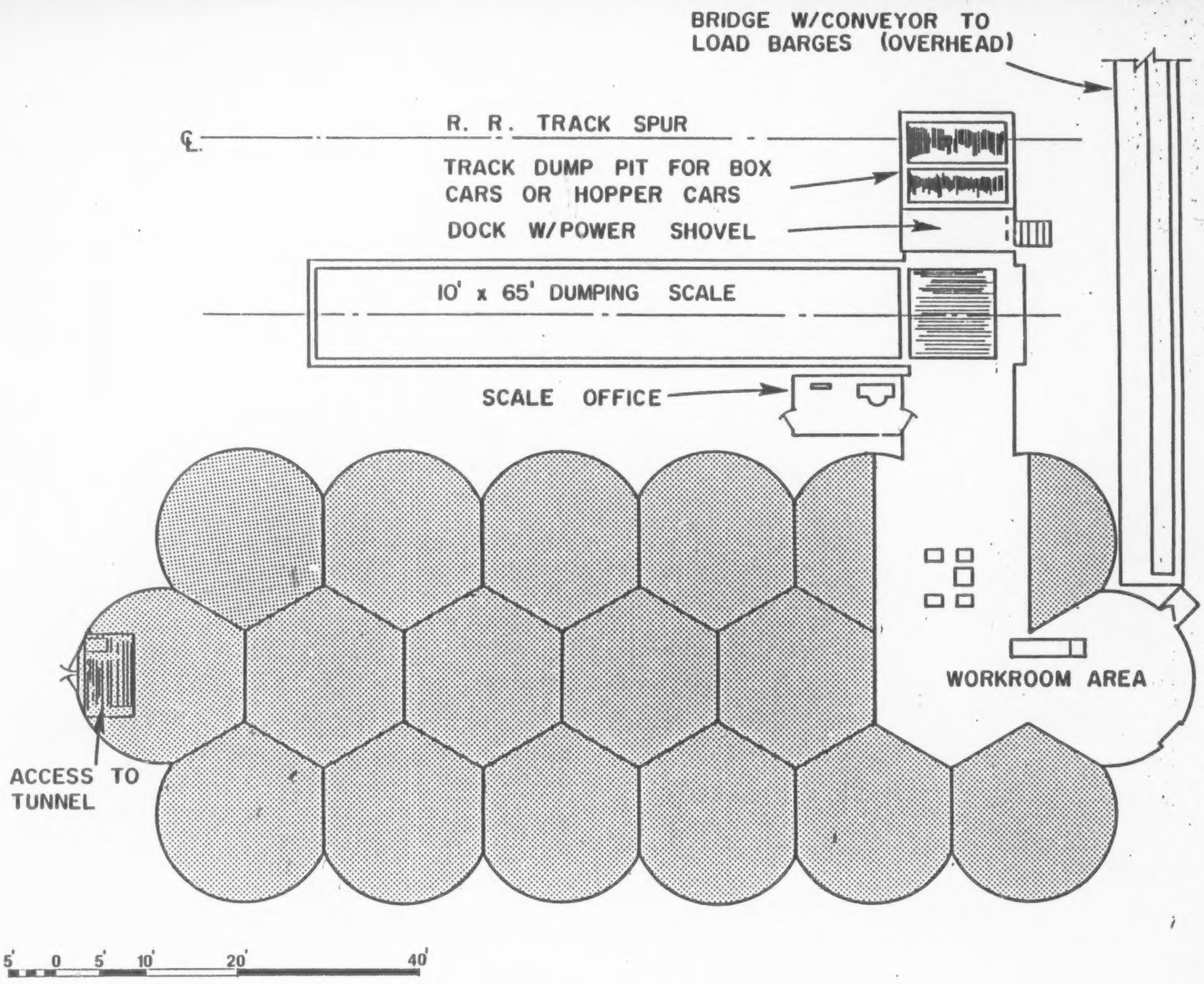

Heads
Distributor
25 Bu Automatic Scale
Overflow Spout
Distributor
Free Spout
8 Bins
2 Bins
2 Bins
Wet Grain Bin
4 Bins
3 Bins
2 Legs
Dryer
Cleaner
Dry Grain Bin
4 Bins
Track Load Out Spout
Truck Loading
Truck Loading
Track Dump
Truck Dump
Belt Conveyor
Boots

Figure 2. Country elevator grain flow schematic.


BRIDGE W/CONVEYOR TO
LOAD BARGES (OVERHEAD)
℄
R. R. TRACK SPUR
TRACK DUMP PIT FOR BOX
CARS OR HOPPER CARS
DOCK W/POWER SHOVEL
10' x 65' DUMPING SCALE
SCALE OFFICE
WORKROOM AREA
ACCESS TO
TUNNEL
5' 0 5' 10' 20' 40'

GROUND LEVEL PLAN

Figure 3. River terminal elevator design with truck and rail receiving and shipping, river barge loading, automatic bulk scales, diverter type sampler, and 3-bucket elevator legs; 500,000 bushels of storage.

CLEANING

Grain cleaning is the removal of foreign material, shriveled kernels, and broken pieces of kernels from the grain by mechanical seiving or pneumatic separation. Although it is easy to cite advantages of clean grain, many elevators do not own grain cleaning equipment and of those that do, many do not use it on anything like a regular basis. In spite of what appears to be low usage, a great variety of equipment is manufactured for cleaning. A recent report indicated that about 1600 different cleaners were available for commercial use from domestic and foreign manufacturers (Chung, 1986).

The most common types of cleaners in use are the mechanical screening and scalping devices. Scalpers remove material larger than the wheat and allow the wheat to pass through. Smaller screens are used to retain the wheat and allow the small weed seeds, dirt, chaff, etc to pass through. The screens may be stationary with the grain flowing or being swept along them, or they may be shaken or rotated. Aspirators separate grain from less dense material by drawing air over a falling grain stream and pulling the light material, or liftings, into a cyclone type separator. Cleaners may be permanently installed or portable, and may utilize more than one type of separation.

According to data compiled by the Japanese government on wheat imports for 1983-87, U.S. wheat contained twice as much "takeout" material, including dockage, foreign material, and shrunken and broken kernels compared to wheat from Canada and Australia. Cleaning of wheat in the U.S. is not a common practice, except at its final domestic destination, the flour mill. In a recent survey by Kansas State University students, only

15% of central Kansas elevator operators said they presently use grain cleaning equipment. Wheat was reported to be the principal grain handled by the 72 elevators surveyed. Those who do not clean grain cited a variety of reasons including not having facilities, high costs of equipment, and the perception that the costs would exceed benefits. However, those same managers thought that cleaning would improve their grain's marketability and were aware of other benefits from cleaning.

Although elevator operators or farmers might think first about the expense of cleaning grain, there are a number of benefits or cost advantages for cleaning (Reichenberger, 1987). Indeed, there must be economic justification for purchasing, installing and using grain cleaning equipment or a grain handler will not likely be interested. Following are some justifications for grain cleaning: There are fewer mold and insect problems in cleaned grain because cleaning removes insects as well as the fines and trash in which insects and molds thrive. Costs of fumigation, spraying and treating are reduced. Cleaning the grain eliminates fine material segregation and allows more uniform and more efficient airflow when the aeration system is operated. Cleaned grain may be improved in grade, is easier to market, and may command a higher price. Shipping costs for the removed dockage and foreign material are eliminated. The screenings themselves can be sold as a feed ingredient, usually for at least half the value of grain. Dockage has a low bulk density so removing it may improve test weight and also creates more storage space in the elevator. Every bushel of dockage takes up the space of two or three bushels of wheat.

Dockage can be removed from wheat much more economically at the producer or country elevator level than further into the marketing system. One study showed that extensive cleaning such as is used for

Canadian export wheat would cost about 14 cents per bushel at an export elevator and about 4 cents at an inland terminal, not including capital costs (Fridirici, 1984). Cost of cleaning with just an aspirator at a country elevator was estimated at 1/4 to 1 cent per bushel. Kiser (1984) concluded that removing about 1% by cleaning was economically sound. An aspirator was determined to have a faster payback than a screener for cleaning wheat.

Cleaning should not be looked at as a cure-all for wheat quality problems. While it can help remove odors, shrunken and broken kernels, improve test weight, etc., it will not remove most kinds of damaged kernels. Heat damaged or mold damaged kernels ususally do not differ in size or density from normal kernels, so they cannot be removed. Wheat damaged by Fusarium head blight or scab tends to by shrivelled or light. Cleaning may remove some of the infected and potentially toxic kernels, but tests have shown only a slight reduction in deoxynivalenol content of scabby wheat after cleaning (Abbas, 1985; Seitz, 1986).

Wheat cleanings are best utilized as animal feed near the point they are removed from the wheat. The feed value of screenings or liftings varies depending on how much actual grain they contain and also on factors like the kind of ration being fed and the proportion of the diet that is grain cleanings. Feeding trials have shown that they do not have any adverse effect on feed intake and are probably most useful in maintenance type rations.

Dust control in grain handling operations is related to grain cleaning as well as to environmental health and safety. Dust control systems typically aspirate air from grain transfer points which generate dust. This dust removal reduces the risk of explosions and reduced respiratory problems for workers. To the extent that the removed dust is not reintroduced in to the grain at loadout, its removal contributes to the cleanliness of the grain.

Dust emissions can also be controlled by adding oils such as mineral oil or soybean oil to the grain. The oil additives do not change grain quality and have no adverse effects when used at approved rates. Typical application rates are 200-500 ppm, which is equivalent to .02-.05%. Most oil treatment is used for corn; wheat is not often treated. Oil is most useful in transfer operations that are outside the elevator, such as loading of barges and railcars. Dust emissions from those operations are sometimes an environmental concern and may be difficult to control by aspiration equipment.

Elevators with dust control systems are generally able to handle liftings and screenings from grain cleaners by running the material into the dust control cyclones and dust storage bins. In many elevators, dust removed from certain points in the handling system is simply reintroduced into the grain rather than transporting the dust to a distant collection point. Recent legislation prohibits adding dust and screenings to grain, except that dust can be removed and then recirculated into the grain at inland elevators. Export elevators may not put dust back into grain.

RECENT TRENDS IN STORAGE AND HANDLING

Most of the recent changes and trends in wheat storage and handling technology have been brought about by the increasingly large carryover stocks and the necessity to store more grain for longer periods. Storage capacity has been increased substantially in the last ten years, both on farms and in commercial facilities. Commercial storage capacity increased

10% in 1986. The last two years have seen a large development of temporary storage structures which generally consist of an aerated pile of grain on the ground with some kind of plastic cover over the pile. The piles are round or rectangular and are bounded by low walls of wood, steel, or concrete. In the fall of 1986 approximately 300 million bushels of grain were stored in such piles, and by summer of 1987 the volume had doubled to over 600 million. Most of the total is corn, with a relatively small proportion being wheat.

Nearly all of the temporary grain storage systems presently in use rely on negative pressure from fans to hold a plastic cover down tightly against the grain. The large surface area makes them extremely vulnerable to wind forces which tend to lift and remove the cover. Small perforated plastic ducts are placed on top of the grain under the cover, and extend through the side walls. The ducts can be connected directly to a fan to simply hold the cover down or they can be left open on the ends and the fans used to draw air through the upper ducts, down through the grain and into the large aeration ducts on the ground.

A few of the temporary or "contemporary" storages are air-supported domes in which there is considerable space between the grain and the plastic fabric roof. Fans keep the inside of the structure under positive pressure with air escaping through roof vents or through the grain into perforated ducts on the floor or ground. Additional fans may be used to aerate the grain. An advantage of the air domes is that air can enter the grain mass uniformly over the entire surface. Automatic fan and vent controls and temperature sensors can be used to open and close aeration duct outlets to bring the grain to the desired temperature. Unlike other temporary systems, domes can be filled and emptied under cover and the surface of the pile is accessible for inspection or sampling at any time.

Observations to date indicate that quality problems from temporary storage structures will probably be a result of moisture leaks, contact with damp soil, too high of initial moisture content, and difficulty in controlling insects in such a large mass. Small tears and punctures in the cover will allow rain to run in and may result in a column or mass of moldy, caked grain below the leak. Some methods used to fill the piles result in fines and foreign material segregating and accumulating in local areas. These accumulations are more susceptible to insect and mold infestation and they divert airflow. When hot spots develop in such areas, it is very difficult to cool them with aeration. Another fairly common problem has been the loss or partial loss of the cover during violent thunderstorms. When electric power is interrupted the fans no longer hold the cover on. Strong winds can then tear it off and the pile is exposed to the rain. This problem can be eliminated by the installation of an emergency backup power generator.

It seems reasonable to expect that the recent trends in grain storage will have an overall negative effect on wheat quality. The increase in temporary storage structures and in farm storage mean that more grain is being place in facilities that are less than desirable for quality maintenance or in the case of farm storage, are less likely to be properly managed. Because grain quality usually deteriorates with time, the longer times for which grain is being stored will result in an increasing amount of low grade grain being brought to market.

INTERACTIONS WITHIN THE HANDLING AND STORAGE SYSTEM

There are considerable interactions between handling and storage technologies based on the size and type of storage structures used. Certain kinds of handling equipment are well suited to high volume upright concrete elevator storages, others to flat storage or to farm storage. These differences reflect different needs for speed, volume, durability, operating costs, labor, etc. but have little if any direct effect on wheat quality.

The equipment and methods used to fill a storage bin have an effect on the performance of the aeration system and on the storability of the grain. Dropping grain into the center of a bin causes the formation of spoutlines which impede airflow. In grains such as corn, with relatively high amounts of fine material, the spoutlines are often removed from upright storage bins by drawing some of the grain out from the bottom of the bin. The first grain to come out will be from the center or core of the bin. This practice, called coring, is seldom used in wheat storages.

In large flat storages, loading from the center or from a loader which is gradually moved backward through the center of the building as the pile is formed, cause similar problems. If grain is piled over each aeration duct by moving the loading device back and forth, airflow will be much more uniform throughout the grain mass. Throwing grain into a pile with mechanical or pneumatic loaders also causes segregation of particle sizes and results in irregular air movement. All of these storage loading problems are effectively eliminated if the grain is cleaned before putting it into storage.

Sampling and inspection of a storage structure can be affected by uneven particle size distribution. Obtaining representative samples or being able to correctly interpret the appearance of samples is made easier by knowledge about the way the grain was loaded.

EFFECT OF OUTSIDE FACTORS

Climate and weather are major factors determining whether or not storage and handling systems are successful in preserving the quality of wheat. Aeration can be used to control insects because insects become less active and do not reproduce at low temperatures. In the southern part of the wheat producing area temperatures may by too high during several months of the year to be able to control insects. In colder areas wheat temperatures can be kept low enough to achieve a high degree of insect control without chemical pesticides. Most wheat is produced and stored in climates where there are large seasonal temperature differences. Those temperature changes are responsible for moisture migration and condensation in grain bins and are one of the main reasons why aeration is essential.

Grain moisture content can be changed slightly by transferring the grain. This is particularly so when moving cold grain during warm, humid weather. Such exposure results in moisture condensation on the cold kernel surfaces. Condensation may be a problem when grain is stored through the winter at a northern location and then shipped in the spring to a gulf export location. The cold grain can gain moisture and weight simply by exposing it to the air in loading and unloading operations.

Rainy, humid weather is rarely a long term situation in wheat areas, but such conditions may necessitate a delay or interruption of aeration. Wheat that is dry enough for safe storage will pick up moisture when aerated in rainy weather, so the storage manager may shut down his aeration during such times.

Wheat is usually harvested at low moisture contents in the southern plains and in the northwest. Because the grain is very dry, mold problems are uncommon and insects do not increase as fast as in grain with higher moisture levels. In the central U.S. there tends to be a south to north gradient from low to higher average moisture contents in wheat at harvest. Because insects and molds grow and develop faster in warm than in cool environments, one would expect they would be more of a problem in the southern states. Moisture, however, appears to be a more important factor because the incidence of both insects and molds in farm-stored wheat increases from south to north in the central states (Sauer, 1984; Storey, 1983). Moisture content also tends to be lower in wheat from western areas compared to eastern areas, reflecting the overall drier climate in the West.

The number of times grain must be handled can be affected by outside factors such as the need for blending to achieve certain contract or grade requirements. Temporary or flat storages may involve multiple handling, including moving the wheat into an elevator for blending or conditioning before it is shipped out. Each handling conributes to mechanical damage and generates dust.

Biological factors such as insect infestation have interactions with storage and handling practices. An obvious ineraction is that handling tends to increase fines and dust which support the develoment of secondary insect pests. Fines in spoutlines also increase the risk of mold problems. Certain kinds of handling equipment like drag conveyors and u-trough screw conveyors tend to accumulate fines, which can serve as insect breeding areas. When a protectant insecticide is to be applied to grain as it goes into storage, consideration should be given to the best place to apply it. Applying the insecticide ahead of a bucket elevator or drag conveyor should result in less chemical loss compared to adding it as the grain enters a grain thrower. Excessive loss of insecticide to the atmosphere reduces the treatment effectiveness and raises concerns about environmental and worker safety.

Biological variability in wheat or in the pests that attack it in storage may merit some consideration in storage management, but it is a relatively minor concern. There is reason to believe that some wheat varieties may be more resistant to insects or molds, but the differences are relatively small compared to other variables. No varieties have been identified or promoted as being superior in storability. Some consideration might be given to geographic differences in pest populations. Warmer climates allow stored grain insects to survive in a wide variety of natural habitats, so there may be a continual pressure from such populations to invade stored grain. Probably a greater source of both insects and molds is the emptying or transferring of bins containing infested or moldy grain. The insects and mold spores may then contaminate other grain.

Financial factors that affect wheat handling and storage technology include construction and equipment costs, interest rates, state of the agricultural economy, storage payments, and the expected risk of price discounts as compared to the cost of quality maintenance. Recent increases in temporary storage systems reflect what is perceived as a relatively short-term need for additional storage space. Government payments for storing grain are a source of income for warehouse operators. Most of the temporary structures can be paid for with one year's storage income. Expected storage times of several years can result in a large income from storage payments if the grain can be kept in marketable condition.

A disincentive to maintaining wheat quality is that considerable damage may occur before it is reflected in an overall change in grade. For example, wheat can be put into storage as No. 2 wheat with 0% damaged kernels and a total of 1% foreign material and kernels that are shrunken or broken. Mold and insect activity during storage could cause up to 4% of the kernels to be classified as damaged before the wheat would be downgraded to No. 3. Further, the warehouse operator has the option of blending the high-damage grain with low-damage grain to keep it as Grade No. 2.

Political influences on grain storage technology and grain quality are in the form of grain grading standards and government programs for grain production and storage. To the extent that government incentives increase or decrease grain production, they affect the size of carryover stocks and the length of time grain might be stored. Recent high productivity and reduced disappearance of wheat and other grains has forced the industry to find a means of storing volumes of grain that greatly exceed available space. The Farmer-owned Grain Reserve program of the late 1970's resulted in large increases in on-farm storage by providing low interest loans for bin construction, loans on the amount of grain stored, and storage payments for up to five years on the grain. Storage payments for government-owned stocks, presently about 3 billion bushels, have been the stimulus for construction of temporary storage systems. Government storage payments which total about $1 billion annually, can represent a significant percentage of a grain merchandiser's income, so he tends to respond quickly to take advantage of changes in government programs.

The Federal Grain Inspection Service is responsible for establishing or changing grading standards and for assuring that grain is uniformly graded according to those standards. FGIS has recently proposed many changes in grade factors or in grading procedures. The grain industry as a whole opposes most proposed changes, preferring to stay with the status quo. Frequent attempts to tighten the tolerances on live insects, for example, have been met with great opposition and no major change has been made. A significant change occurred in wheat grading in 1987 when the procedure for reporting dockage was changed so that the actual amount is reported to the nearest 0.1% rather than rounding to the next lower 0.5%. A sample with 0.49% dockage would be reported as having 0% dockage under the old reporting system and 0.5% under the new system.

The change in wheat dockage reporting has a significant effect on the way grain is treated. Grain cleaning now makes more sense economically, and it is likely that the average amount of dockage in wheat moving through the marketing system will decrease. The new prohibition against adding dockage and foreign material to grain should also result in cleaner wheat. Data compiled by the Japanese shows that wheat they imported from the U.S. in recent years contained 2-5 times as much dockage and foreign material as did Canadian and Australian wheat. The new regulations should make this comparison more favorable to the U.S. in the future. Export grain is routinely cleaned in Canada and Australia, but not in this country.

Wheat producer organizations are encouraging the Commodity Credit Corporation to pay a small premium for wheat that contains more that the minimum percentage of clean sound grain for Grade 1 or 2 wheat. They think that a positive approach in the form of price incentives rather than the usual negative or penalty approach through price discounts will stimulate the delivery of clean sound grain from the farm or country elevator. Since CCC is the largest buyer of wheat, such a policy could have a significant effect on the overall quality of U.S. wheat.

STRENGTHS AND WEAKNESSES OF THE PRESENT TECHNOLOGIES

Many positive things can be said about the present technology for handling and storing wheat. Equipment and techniques are available to maintain the quality of the grain from the combine to the end user even if the time between those two points is months or years. Factors that result in low quality wheat being marketed are in the nature of lack of incentives for quality or lack of penalties for poor quality. The present excessive supplies of all grains and low grain prices also tend to make quality concerns secondary.

The use of aeration in both farm and commercial storage has increased in recent years. A wide variety of equipment is available and information on its proper operation is available from manufacturers, extension publications and research papers. Temperature monitoring and recording systems have been available for many years and have gradually become a common part of commercial grain storage management. Many larger or more conscientious producers who store their own wheat also rely on temperature measurements to detect problems or manage aeration.

The recent expansion of temporary storage should be viewed as a weakness in terms of relating technology to grain quality. As grain production and demand approach a more normal balance we can expect a decrease in this kind of storage.

Much of the commercial grain business is geared to high-speed, high-volume handling rather than toward gentle handling and avoidance of kernel damage. Although this has contributed to quality problems in corn because of breakage and dust, it is not a major concern in wheat.

The disappearance of liquid fumigants has taken away an easy-to-use weapon in the battle with stored grain insects. While this may result in some cases of increased insect damage, it can also be looked at as a stimulus to use other insect control methods which have a more positive effect on overall grain quality and cleanliness. Grain cleaning, aeration, temperature monitoring, and regular inspections can prevent or minimize insect problems.

NEW OR EMERGING TECHNOLOGIES

There is little that is really new in grain storage technology, but some technologies have been recently improved or recently applied. Programmable controllers for aeration systems are now available. These systems monitor ambient temperature and humidity as well as grain temperature and can be set up run aeration fans when conditions are favorable until a desired grain temperature is reached. These controllers should reduce management errors such as not moving a cooling front completely through the grain or aerating when weather conditions are unsuitable. The result should be savings in energy costs and improved grain quality.

Inert atmosphere storage systems have been marketed recently. As sealed, nonaerated storage units, they have the potential for moisture migration problems and leaks, but the concept of a tightly constructed, sealable structure has definite advantages for effective fumigation. Such structures can be fumigated with conventional fumigants or with inert gases such as carbon dioxide or low oxygen burner gases from exothermic inert atmosphere generators. Inert atmospheres kill insects rather slowly, so a tightly sealed bin is required to contain the gas. This technology has been used in higher value commodities such as nuts and raisins, but has been considered too expensive to be widely used for grain.

The low-cost temporary storage systems might deserve mention as an emerging technology, but not necessarily in a positive sense. The experience gained from working with these structures may produce some new construction techniques or aeration technology that will improve traditional storage or reduce the cost of flat storage without increasing the risk of quality loss. In the short run, however, temporary storage will remain a concern with regard to grain quality.

The promotion of good grain storage practices has been a goal of extension specialists for years, but recently there has been greater interest in such programs. An integrated approach to grain storage management and the use of demonstration projects to show the effects of good and poor management have been tried in several states. Private agricultural consulting firms have also gotten involved in grain bin inspection, pest management and grain aeration. These new trends should produce an increased awareness and interest in grain caretaking on the part of farmers.

SUMMARY:

Movement of grain may adversely affect quality by causing physical damage such as breaking, cracking and abrasion, or by exposing the grain to moisture or biological contaminants such as insects. Physical damage is a very minor problem in wheat compared to corn or soybeans, so wheat handling equipment and facilities may not be designed with gentle handling as a major concern. Storage involves protection of the grain from the weather and prevention of infestation by insects, molds, and rodents. Aside from a well designed and constructed storage structure, an adequate aeration system is the most important factor in maintaining quality of wheat in storage.

Aeration is an effective and economical way to control temperature and moisture, and thus limit insect and mold development. Both positive and negative pressure aeration systems are in use, each with certain advantages and disadvantages. Existing aeration systems are not always used effectively or efficiently, especially at the farm level. Temperature gradients which occur in nonaerated or improperly aerated grain, and cause moisture migration, are a greater risk in large bins than in small ones. Physically moving or turning grain from bin to bin has long been used as a substitute for aeration and also as a means of blending to achieve uniform quality and moisture throughout a large lot of grain that is to be stored or sold.

Storing grain in sealed structures or with refrigeration or with chemical mold inhibitors has not seen wide use in the U.S. because of high costs or failure to maintain the desired grain quality. Traditional storage methods have proven more effective and economical for storage of wheat, even though there has been considerable research effort and commercial promotion

of alternative technologies in the U.S. and in other countries.

Temperature monitoring is a widely used and highly desirable management tool in grain storage. Thermocouples attached to cables in the grain are read individually or they can be recorded automatically at predetermined intervals. Increases in temperature that are not explainable by outdoor conditions are a warning of insect or mold problems that should be corrected. Some temperature monitoring equipment is used in conjunction with programmable controllers which operate aeration fans to cool grain when needed.

Bulk grain is moved with a variety of mechanical and pneumatic devices. The screw auger conveyor is a relatively inexpensive and portable device that is widely used on farms and in flat storage structures. Commercial elevators rely mainly on belt conveyors for horizontal movement and belt bucket elevators for vertical movement of grain. Grain damage in handling is increased by low grain temperature, low moisture content, hard impact surfaces, and high grain velocity at impact. Some kinds of handling equipment like screw augers are more likely than others to damage grain. All of these variables are relatively unimportant for wheat, however, since wheat is highly resistant to breakage compared to corn and soybeans.

Grain can be cleaned by passing it over screens or by pulling air over a falling grain stream to remove small or light material. Until recently, relatively little wheat was cleaned except by the final buyer, the miller. Changes in the reporting of dockage in grain inspection now make it more economically justifiable to remove dockage from wheat. Other benefits from cleaning wheat include lower costs for quality maintenance in storage, and improvement in quality and price received. Canadian and Australian wheat in export markets contains half as much dockage, foreign material and shrunken kernels compared to U.S wheat.

The technology involved in grain handling and storage is relatively simple. With few exceptions, quality problems that exist in wheat marketed in the United States or to our export customers could be remedied by the application of existing technology. Poor quality grain is marketed because the marketing system and the grading system do not adequately discourage or prevent it. Buyers do not often offer significant premiums for extra sound clean wheat, and marketing strictly on the basis of grades encourages sellers to blend dirty or defective grain with sound grain to the limit allowed in the grade. Recent changes in the dockage reporting procedure and the prohibition against adding screenings back to grain should improve the cleanliness of U.S. wheat.

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Background Paper No. 4

The Interactions of Corn and Soybean Quality with Grain Storage

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1. INTRODUCTION

Surplus supplies are forcing grain handlers and the U.S. government to store grain for increasing lengths of time. As of September 1, 1987, the United States Department of Agriculture estimated that there were 4.88 billion bushels of corn and 436 million bushels of soybeans in storage carrying over to the 1987-88 marketing year. This represents 65% and 22% of anticipated use, for corn and soybeans respectively (Iowa Agricultural Statistics, 1987). These carryovers coupled with production estimates nearly equal to consumption assure that, for the foreseeable future, grain will be in storage a year or longer. Grain is a perishable commodity with a finite shelf life. Shelf life is the length of time a product can be stored without economic loss of functionality. Storage will always expend shelf life and will never improve quality.

Storage affects grain quality in several ways. This paper explores the interaction between grain storage and subsequent quality. Storage occurs in two general situations throughout the grain distribution system--1) in buildings or piles for future marketing and 2) in transportation carriers enroute to a destination. For grain in international commerce, both situations are important in determining quality changes. This contrasts with domestic trade, for which in-transit times are often short. Because grain destined for international markets will always be dry, high-moisture preservation (for domestic feed markets) will not be discussed.

The objectives of this paper are to summarize current knowledge about the relationship of grain quality factors to in-storage deterioration, and to assess the potential for new technology and Standards changes to reduce in-storage losses

2. PRINCIPLES OF STORAGE

2.1. Biological Principles

Biological agents (fungi, insects, bacteria) are the primary cause of quality deterioration in storage. Insects and their control are discussed in another article; the major focus of this paper will be on fungi and bacteria. In-storage spoilage affects grain quality in three ways--1) creation of damaged kernels, those that will be graded in the total or heat-damage category in the Grades; 2) loss in dry matter, with an accompanying decrease in density; and 3) potential deposition of toxic substances.

The classic work in determining parameters for safe corn storage was done at Iowa State University. Increases in damaged kernels and reductions in test weight were exponentially related to grain moisture content and temperature (Steele et al., 1969). This research led to equations for the "Allowable Storage Time" table (Thompson, 1972), reproduced in tabular form in many handbooks of grain storage (MWPS, 1980a). Table 2-1 shows the Allowable Storage Time for corn. At the end of the Allowable Storage Time, corn will be on the verge of dropping one commercial grade number as a result of increases in damaged kernels, and will have lost about 0.5% of its original dry-matter weight. The dry-weight loss arises from the decomposition of glucose units to water and carbon dioxide (Steele et al., 1969).

$$C_6H_{12}O_6 + 6O_2 \dashrightarrow 6H_2O + 6CO_2$$

Grain temperature °F	Corn moisture, percent						
	18	20	22	24	26	28	30
	---------days---------						
30	648	321	190	127	94	74	61
35	432	214	126	85	62	49	40
40	288	142	84	56	41	32	27
45	192	95	56	37	27	21	18
50	128	63	37	25	18	14	12
55	85	42	25	16	12	9	8
60	56	28	17	11	8	7	5
65	42	21	13	8	6	5	4
70	31	16	9	6	5	4	3
75	23	12	7	5	4	3	2
80	17	9	5	4	3	2	2

Table 2-1. Allowable Storage Time for Corn (MWPS, 1980a)

Steele noted that hand-shelled corn had Allowable Storage Times 2-3 times longer than broken corn but made no attempt to quantify the breakage levels of corn in this study, beyond "average combine run" with about 20-30% of kernels showing some sort of pericarp damage.

A 0.5% weight loss represents about 1 cent per bushel, for corn at $2.00/bu. This is a significant fraction, perhaps 20%, of the elevator's typical handling margin. In addition, for every gram molecular weight of glucose (180 g), 677.2 kilocalories of heat are liberated. Therefore, neither the grain temperature nor the moisture content in a spoiling mass will remain constant (Christensen and Meronuk, 1986). The carbon dioxide represents weight loss unrecoverable by any form of blending. Recent work has confirmed the general concept of the Allowable Storage Time, but also proved that mold toxins can be produced before the Allowable Storage Time is reached (Fernandez et al., 1985). Because storage conditions never remain constant, the Allowable Storage Time data has never been validated in storages but has received general acceptance as criteria for storage.

The biological parameters causing mold invasion have been presented by Christensen and Kaufmann (1969). In essence, a grain moisture in equilibrium with 65% air relative humidity is necessary to support activity. There are many species of fungi at work in stored grain, and each has its own requirements for growth. The

Aspergillus flavus species responsible for producing aflatoxins requires a humidity of 75-85% (Christensen and Meronuk, 1986; Armolik and Dickson, 1956). Others will grow at the lower humidities and lower temperatures. Microbiological analysis is a recommended method for establishing the storage history of a grain lot (University of Minnesota, 1977).

The original Allowable Storage Time table stopped at 18% moisture because of the long time periods required to collect low-moisture grain data. Mathematical modelling has been used to extrapolate Saul's data to low moistures (Thompson, 1972). The validity of this extrapolation has never been checked. The relative humidity principle suggests another criterion for establishing storage risk--moisture content in equilibrium with 65% relative humidity. Equilibrium relative humidity is given by the equation (ASAE, 1986):

$$RH = 1 - \exp\left[K(T+C)(M)^{N}\right] \qquad (2\text{-}1)$$

where:
RH=relative humidity, decimal
T=temperature, ^{o}C
K,N,C=constants
M=moisture content, % db

with standard errors of 2-8% relative humidity for various grains.

Experimentally derived values for the constants are given in Table 2-2. The practical consequence of equation (2-1) is shown in Figure 2-1, graphs of moisture content (wet basis) in equilibrium with 65% and 80% relative humidity at increasing temperature.

These graphs have important ramifications in evaluating quality losses in transit and in deciding where geographically long-term storage should be concentrated. The U.S. export corn market is largely based on 15% moisture corn or less, but even 15% is not safe at higher temperatures.

Grain	K	N	C
Corn	8.6541×10^{-5}	1.8634	49.810
Soybeans	30.5327×10^{-5}	1.2164	134.136

Table 2-2. Constants for the equilibrium moisture content equation (ASAE, 1988)

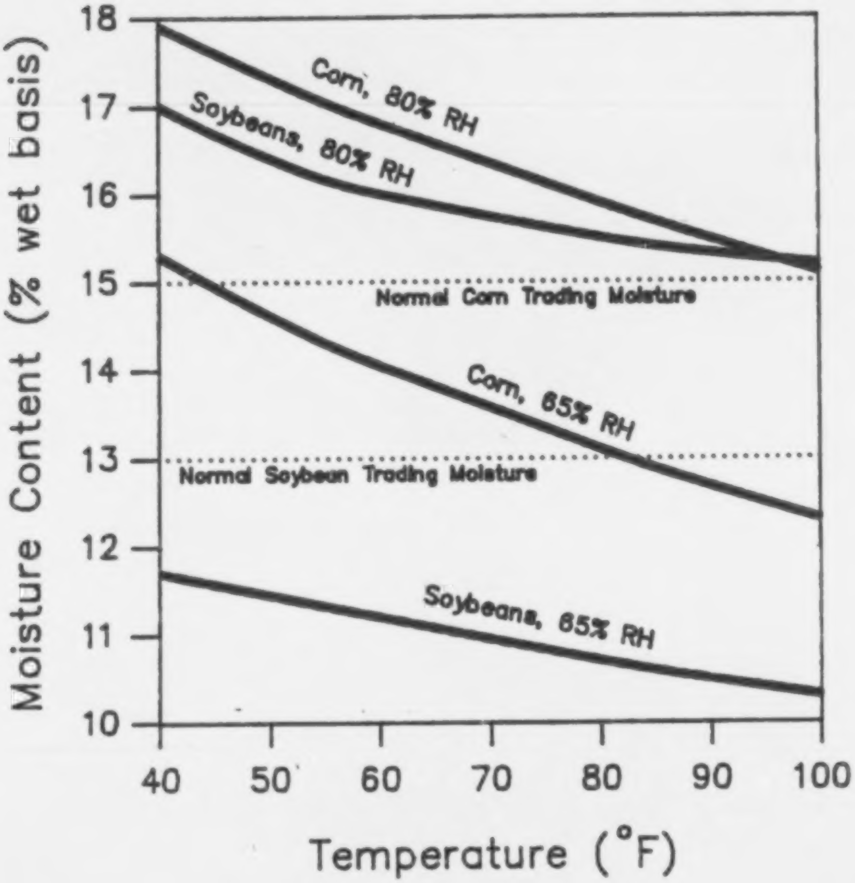

Figure 2-1. Corn and soybean moisture contents in equilibrium with 65% and 80% relative humidity.

Several important conclusions relative to quality can be formulated from the biological principles of storage.

1. Shelf life of grain is a finite time-line, with a certain share expended at each storage condition. There is no rapid means of determining what share of total shelf life remains. Microbiological assays can be used if time and cost are not limiting factors.
2. The moisture conditions required to control the rate of deterioration are not totally compatible with present standards and trade practice.
3. Grain quality factors, primarily breakage and foreign material levels, may affect the rate of deterioration at given environmental conditions, but cannot be relied upon to prevent deterioration.
4. Unaerated grain in extended transit will undergo a progressive shortening of shelf life because there is no way to dissipate the heat generated by microbiological activity.
5. Deterioration rates are exponential with temperature and moisture content. Therefore, the time required to generate a fixed percentage of damaged kernels gets progressively shorter as overall damage levels increase.

2.2 Aeration Principles

Control of temperature and moisture is fundamental to preserving quality. Even assuming that these parameters are uniform in a grain mass, they will not remain so over time. Moisture will migrate in response to temperature differentials, as shown in Figures 2-2 and 2-3.

The consequence of moisture migration is that grain lots assumed to be in storable condition will not remain so. The cold weather migration (Figure 2-2) primarily affects grain in domestic storage, causing deterioration as temperatures rise in the spring. Warm weather migration (Figure 2-3) is particularly vexing for grain shipments, both from cold to warm areas of the USA and from the USA through warm waters to overseas destinations. A barge or vessel is a moving storage bin and will have the same migration phenomena as land- based bins.

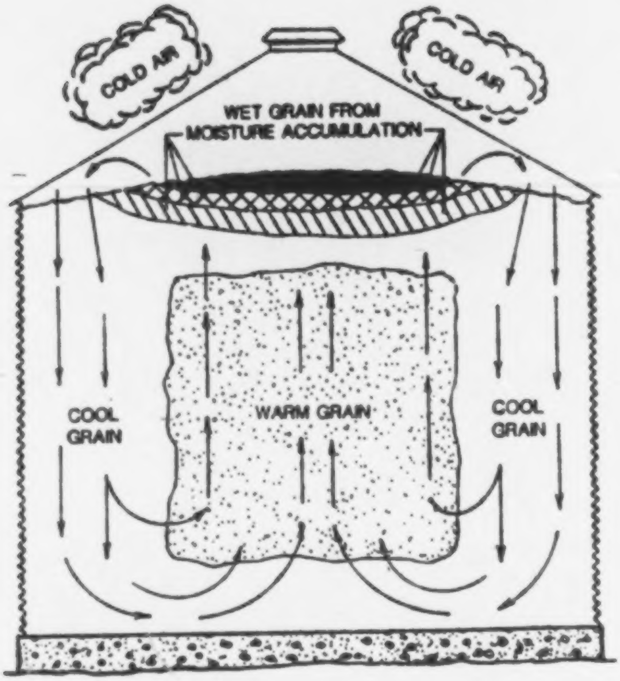
COLD AIR
COLD AIR
WET GRAIN FROM
MOISTURE ACCUMULATION
COOL
GRAIN
WARM GRAIN
COOL
GRAIN

Figure 2-2. Moisture migration patterns in falling temperatures (Foster and Tuite, 1982)

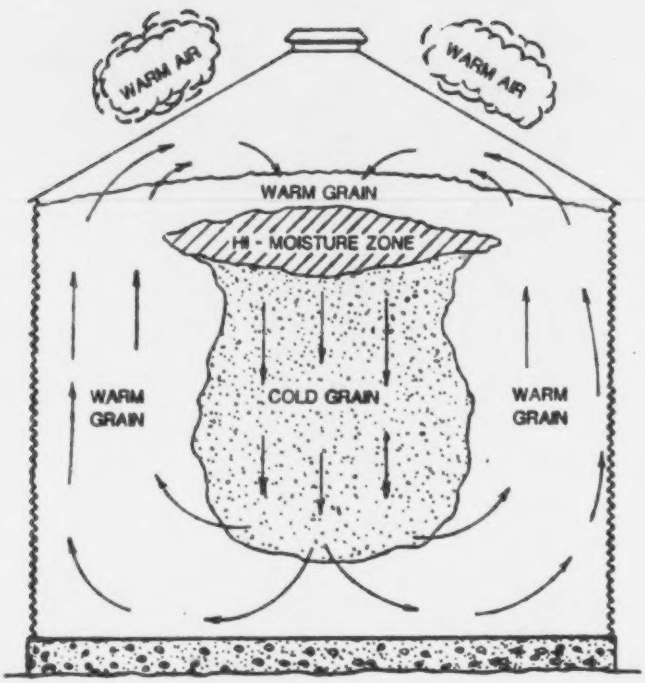
WARM AIR
WARM AIR
WARM GRAIN
HI - MOISTURE ZONE
WARM GRAIN
COLD GRAIN
WARM GRAIN

Figure 2-3. Moisture migration patterns in rising temperatures.

(Foster and Tuite, 1982)

Equalization of temperatures through aeration is the remedy for moisture migration, with a 10-15°F average differential between grain and air being the normal criterion for operating fans (MWPS, 1980b). Grain in transit, however, cannot be aerated, and ventilating the top of barges, vessels, etc., does little to either remove moisture or heat. The only protection in these cases is uniformly low moisture content.

Aeration removes the driving force for moisture migration and also carries off heat generated by microbiological activity. The usual recommendation is 0.1 cfm/bu or more. This airflow will equalize grain and air temperatures in 150-200 hours depending on the season. Other airflow rates require proportionately different times.

The management of aeration systems has a major effect on quality. Storages without aeration are incapable of assuring quality over any extended period. Because energy costs for aeration can be 1-2 cents per bushel annually (Hurburgh, 1987a), the natural inclination of warehousemen and growers operating on narrow margins is to reduce operating times as much as possible. Unnecessary operation uses energy and also causes moisture shrinkage up to 1 percent of original weight (Hurburgh, 1987a). Insufficient operation creates the potential for hot spots and damage increases.

It is also possible for aeration systems to be so undersized as to be incapable of removing heat as fast as the grain microorganisms generate it. At this point, the grain will continue to heat. Its shelf life continues to fall, despite the efforts of the warehouseman to control it. The airflow at which this happens can be calculated from mathematical models of mold invasion and heat-balance equations (Thompson, 1972). In general, airflow in commercial and on-farm systems exceeds these threshold values on average but often does not in certain areas within the storage mass.

If grain contains fines, which block the air spaces and increase pressure resistance to airflow, air distribution will not be uniform, and total airflow will be less. Hurburgh (1987a) developed data to show that the airflow in a spout line (area of high fines concentration directly under a spout) would be 0.01-0.02 cfm/bu when the bin average was 0.1 cfm/bu, assuming No. 3 yellow corn, 4% broken corn-foreign material (BCFM). This is well under the "critical" airflow for many moisture-temperature combinations. Particles 10/64" in diameter and smaller cause the greatest increase in airflow resistance (Grama et al., 1984). Overaeration of an entire mass to compensate for shortages in localized areas can add 50% or more to the annual energy cost, in the order of $10,000 per year for a 500,000 bushel storage (Hurburgh, 1987a). Anderson (1973) presented actual cost data showing a sixfold increase in aeration costs for No. 3 yellow corn compared to naturally dried No. 1 yellow corn. He attributed most of the increase to the larger spout line in the No. 3 corn.

The geometry of certain storages (conical piles, oval stadium storages, etc.) virtually guarantees nonuniform distribution of airflow. Prediction of airflow under nonlinear conditions was first developed by Hukill and Ives (1955), but there is a need to expand this work and apply it to current storage designs.

2.3 Storage Practice

Most dry grain storage in the USA is in upright bins, silos, steel buildings, or confined piles. As of September 1, 1987, about 46% of the stored corn stocks and 25% of stored soybean stocks were held on farms, with the balance in commercial warehouses (Iowa Agricultural Statistics, 1987). The percentage of grain stored on farms is declining as the carryover increases and commercial warehousemen construct low-cost storage in response to government program incentives. On-farm grain systems are typically not sized for storage of more than a single year's crop. The construction cost of new farm storage, is higher than that of large commercial storage (approximately $1.00 per bushel versus $0.40) because farm units are smaller. Grain storage is not the only item in which a farmer can invest capital, whereas it is the primary component of a warehouseman's business. The cost statistics have important implications for quality because the USA can anticipate increasing amounts of grain in lower-cost, less- manageable forms of storage. The transitory nature of government storage dictates that new storage should be paid for as quickly as possible. Furthermore, an open market with no government storage incentives would not demand as many storage services.

2.3.1. Upright bins and silos.

The most easily managed type of storage is in upright bins or concrete silos. There are aeration floors or ducts in the bottom; fans either pull air down or push air up. Storage sizes range from farm bins as small as 3000 bushels on farms to more than 500,000 bushels at commercial warehouses. Farm bins are more likely to have oversized aeration systems because the smallest available fans will deliver more than 0.1 cfm/bu to small storages. On the other hand, a USDA study revealed that, despite readily available information on aeration management, most farm aeration systems were either not operated at all or not operated sufficiently (Storey et al., 1983). The size and depth of commercial storages cause aeration systems to be sized much closer to operational minima, giving the warehouseman less leeway for management errors and less flexibility to select aeration times to minimize moisture loss. Commercial upright storages often have temperature detection equipment while farm storages do not.

The presence of temperature sensing cables is a major advantage for commercial systems. Thermocouples are suspended in about 10' vertical increments in 5-10 places within the bin. A computer or a manual reader is used to remotely read the temperature values. The cost of these systems is more easily recouped in large storages. A $20,000 system for 500,000 bushels is much more cost effective than a $2,000 system for 20,000 bushels.

Upright storages can be "turned" (grain moved) easily provided that there is empty bin space to work with. Turning will break up hot spots but also causes extra breakage and shrink. Industry sources indicate that a turning costs about 1 cent per bushel creates about 0.5% BCFM, and generates about 0.1% weight shrink.

A detailed discussion of aeration system design is beyond the scope of this paper. However, it is necessary that perforated open area be sufficient to provide reasonably uniform air distribution. Airflow uniformity and ease of filling/emptying are the major reasons for using round upright structures. In bins without complete perforated floors, there will be grain near the floor that will not be aerated. It is important that dry grain be on the bottom of bins. Farm bins that are used for both drying and storage will generally have full perforated floors.

The issue of push-up versus pull-down aeration systems has been debated for many years. From a quality viewpoint, the argument for push-up systems is that moisture will be concentrated at the top where it is most manageable. Heat from moisture-migration-induced spoilage will not be carried through the grain. Push-up systems require roof ventilation to prevent condensation from dripping back on the grain. The pull-down system avoids the roof condensation problem and is promoted as a good system for monitoring quality, by odor of air. This is a weak argument, in the author's view. There has been no study documenting comparative energy usage or airflow distribution.

2.3.2. Flat and pile storage

The recent demand for storage space has increased the number of so-called nontraditional storage structures. These include large steel warehouses, outdoor piles on hard surfaces confined by movable sloping walls or circular rings and several forms of on-ground piling. All these storages are more difficult to load, unload, and aerate. Their advantage is lower initial cost, typically half or less than comparable upright storage. The major implications for quality are increased spoilage risk, possible inclusion of dirt, stones, etc., additional handling (especially in unloading), and little operator flexibility in managing or monitoring problems.

Large steel buildings ("flat storage") have long been used for extended storage. They are filled from conveyors in the roof and employed with portable augers or payloaders. Aeration is introduced through ducts; air distribution is not as uniform as in round bins. Successful users of that storage have stored clean, sound grain (Twomey, 1987). Grain is spread over a large area to a shallower depth (20 ft or less) than in upright bins, making the installation of temperature monitoring cables more costly and the quick removal of hot spots unfeasible.

Contained piles are usually covered with vinyl tarps. Draw-down aeration systems create negative pressures under the tarp to hold it down in windy conditions. The need to retain the tarp restricts the airflow through the pile. Aeration is often insufficient. The tarps can either be put on first (cover-on-first systems) and be raised with the pile or be put on last. There is no evidence supporting either method as better.

A major source of quality problems is leaky tarp installations. There is even less flexibility in correcting localized spoilage in these systems than in flat storage. Therefore, anticipation of remaining storage life is the most crucial decision the warehouseman has in choosing what grain to put in storage. The Standards do not provide this information. The usual warehouse application of the Standards encourages the storage of the lowest possible quality that will meet the specifications (No 2. or No. 3 corn). The warehouseman expects that any damage increase can be blended off with other grain. Detailed data on storage experiences are rarely put into the public domain.

Uncovered piles are used for temporary storage of corn. While there is no formal data on the amount and use of uncovered piles, industry sources state that they are used only as a last resort. As such, they may or may not be aerated. Rain will penetrate approximately one foot into the grain. Uncovered piles should be as smooth as possible and should not put out until the average temperature is 40°F or less (Parrington, 1983). There is no capability to cool large hot spots on unaerated, uncovered piles. Portable aerators can only reach up to about 6 feet into the pile. THeir value is limited to controlling surface problems. Unsanitary conditions (rodents, bird droppings, etc.) can occur in uncovered grain piles.

About 900 million bushels of nontraditional and flat storage were added in 1985-1987 according to trade sources. Nontraditional storage is storage in structures and without permanent roofs. Expansion of nontraditional storage has created a dilemma for some elevators that has major implications for quality. If the elevator has more high-risk storage than it does merchandising and handling work space, then it may be unable to move grain going out of condition. The spoilage will get worse, and eventually much lower-quality grain will reach the market. For example, an elevator with 500,000 bushels of work space and 4 million bushels of pile storage would have little ability to move the piles quickly. These situations did occur in 1986-1988, although few records were kept, for obvious reasons.

The incentive to put grain in low-cost quick-payback storage magnifies the marketing incentives to provide the lowest possible quality allowed under the standards. Storage managers must take the risks of balancing conflicting signals. Whenever those risks go bad, all grain users lose in that greater quantities of defective grain are received than otherwise would have been.

3. QUALITY LOSSES IN STORAGE

No reduction in quality in storage is beneficial to any user. Quality, by any definition, changes for the worse. The Grain Standards do not provide any information about remaining storage life or past storage history.

3.1 Weight Reduction

The chemical formula showed that weight was lost from metabolic deterioration, whether by fungi or insects. If we accept the Allowable Storage Time as predictive of deterioration rate, then, for every 2-3% increase in damaged corn kernels (the increment corresponding to one grade number), 0.5% of corn dry matter (about 0.45% of total weight at 15% moisture) will be lost. An increase from 2% damage to 7% damage represents about 1% weight loss, unrecoverable by blending because it is dry matter and a severe complication to maintaining warehouse inventories. the elevator may only have 2-3% margin to work with.

Moisture weight is also lost from routine aeration. When grain spoils, it heats. The heat liberated over the Allowable Storage Time is capable of evaporating additional water. This explains the apparent dichotomy that heating grain eventually reaches a very low, ostensibly stable moisture content -- yet another proof that moisture content at the time of inspection is not a good indicator of either storage history or future risk.

Kernel weight and kernel density also reflect loss in dry matter. Unpublished in-house data from a grain company shows a 7 lb/bu reduction in test weight and a 10% loss in thousand-kernel weight of mold damaged corn kernels versus undamaged, as sorted by inspectors from samples of market corn. Similarly, Storey et al. (1983) reported a 1-2 lb/bu test weight loss in the entire grain mass from uncontrolled in-storage insect infestation.

3.2 Damaged Kernels

Obviously, insect and fungi invasion cause an increase in damaged kernels, as defined in Grades. Additional biochemical changes accompany damage. Iverson (1986) established a linear relationship between free fatty acid (FFA) content of soybeans and damage. Although the data in this study did not contain damage values below 5.5%, it has been extrapolated to predict that the FFA value in U.S. No. 2 soybeans (2% damage) will be 0.7%, just under the oil trading limit of 0.75%. Although unpublished data on low-damage soybeans suggest that the Iverson equation overpredicts damage, the deteriorative effect of molding is evident. It is widely accepted that damage in corn reduces oil content; unpublished data of the author show that virtually all the oil is lost in fully discolored kernels.

Damaged grain may or may not have reduced feed value per unit of weight. Studies have reported varying results. Visually molded kernels have a greater risk of containing one or more toxins, although toxins can be present before the Allowable Storage Time is reached (Fernandez et al., 1985). The same data that showed kernel weight reductions in damaged kernels indicated 50 to 100-fold higher mycotoxin concentrations in the damaged kernels. Thus damage, as measured in current practice, is a risk factor. Inability to distinguish among gradations of damage and species of mold present limits the marketing potential for high-damage (in excess of 10%) corn. Advancing immunochemical technology for rapid detection of specific toxins will offer buyers more protection against risks.

4. INTERACTIVE EFFECTS

This section describes interactions of storage and system parameters on other grain quality factors. The following topics are discussed:

- -Moisture uniformity and drying
- -Broken grains, foreign material
- -Inspection practices
- -Transportation conditions

4.1 Moisture Uniformity and Drying

The importance of moisture uniformity was stressed by Christensen and Kaufmann (1969). They reported instances where fungi were present that could not have thrived had the grain been at the moisture content assumed by the warehouseman. In a barge sampling study, aggregations of 16% moisture corn were found in a barge of supposedly unblended 13-14% moisture corn (DeHoff et al., 1984). The point is that nonuniformity always exists and that deliberate blending of wet and dry grain will magnify the problem. Moisture will never equalize completely. The spread in kernel moistures will be greater with increasing range in the moistures blended (Nugyen et al., 1984). The blending guideline of 4 percentage points established by the Grain Quality Workshop (NAEGA, 1986) was based more on experience than on experimental data.

The ecology of mold growth dictates what will happen if mixed moisture grain begins to spoil. Heat and moisture are given off in sufficient quantities to place surrounding dry grain in jeopardy.

Certain high-temperature dryers, notably those of the crossflow design, produce nonuniformly dried products. The moisture range from a typical continuous-flow cross-flow dryer is about 4-6 percentage points and, from a typical on-farm bin batch dryer, about 6-10 points (Bakker-Arkema, 1987). This adds to the typical 4 to 6 point variation in kernel moistures on ears of corn. Although there is no conclusive data on this point, warehousemen content that the average moisture content of nonuniformly dried grain must be 1-2 percentage points lower for safe storage, Technologies that improve moisture uniformity in dryers will, without question, reduce in-storage damage and will permit higher average moistures to conserve weight and control breakage susceptibility. The exact benefits of uniformity are not known; research to establish properties of blended grain would be very beneficial to the United States.

A single-kernel moisture tester, described in another paper (Hurburgh, 1987b) is the only way to identify blends and variations. Interpretation of this data under various conditions will require considerable study. Hill et al. (1987) found 7 percentage points variation in kernel moistures of export grain, both before loading and at destination. Presumably the distribution of kernel moistures (e.g., normal versus bimodal) will indicate its management history. However, the interpretation of the data for long-term storage decisions as compared with shipment decisions will be different.

Corn dried with heated air supports a higher equilibrium relative humidity than natural-air dried corn (Tuite and Foster, 1963). To maintain the same storage risk, heated-air dried corn must be at a lower moisture content. This finding is consistent with the author's personal experience with farm stored corn. The heated-air statement probably should be modified to mean grain temperature, as some dryers do not elevate grain temperatures even though very hot air is used.

4.2 Broken Grains and Foreign Material

Grain breakage and presence of foreign matter increases the rate at which fungi and insects invade stored grain. Steele et al. (1969) stated that, based on his observations when developing the Allowable Storage Time data, corn containing average amounts of cracked kernels and fines (about 20% chipped kernels and less than 3% BCFM) spoiled 2-3 times faster than clean sound corn. Unfortunately, the effects of physical damage were not quantified. Cotton and Wilbur (1982) summarized several studies showing that insect activity continued in wheat containing dockage even at moisture contents normally too low for insects to survive. The

Steele data are particularly relevant in that they indicate cracked grain, whether from combine or dryer damage, will be much more perishable than sound grain, and not only the times will mold faster. Steele's observation was that the cracked whole kernels were also more susceptible. Thus, control of factors causing cracks would be an effective strategy to prevent in-transit storage losses and to offer customers a more stable product.

These research studies support the common observation that the broken kernels always mold before the whole ones. Gilbert (1987) reported about 75% less fungal and insect deterioration in a pile of cleaned wheat relative to a similarly sized pile of wheat containing 1-2% dockage.

The problems associated with broken grains compound themselves because airflow is diverted around concentrations of fines. Not only will the broken pieces spoil faster, but they cannot be aerated as effectively. Given the practice of subdividing ocean vessel shipments at destination, buyers receiving the spout-line high-fines lots will be dissatisfied about receiving the greater damage as well.

Cleaning would remove most of these problems. Hill et al. (1981) found that most of the inert foreign material in corn is concentrated in sizes smaller than 8/64 inch. Airflow resistance of corn increases most markedly with addition of pieces 10/64-inch and smaller (Grama et al., 1984). Coring, the removal of an inverted cone in the center of a bin, is another effective practice to reduce the effects of broken grain and/or FM. However, coring is not possible in storage structures other than upright bins, tanks, or silos with center draw-offs. In-house data from one grain company indicate that corn particles below 12/64-inch and soybean particles below 8/64-inch are the most likely to form spout lines. Cleaning alone will not ensure that the grain will stay clean. Prevention of breakage before it occurs is the only long-term solution to the cleanliness problem.

Extra handling (turning) to control hot spots is to some extent self-defeating. In a typical elevator, an elevation and subsequent drop increases BCFM levels by 0.25-0.50 percentage points (Hurburgh and Moechnig, 1984) and causes about 0.2% weight shrink (Minary, 1977). Moving grain to cool it may trade one set of problems for another. Numerous authors point out that grain infected with active mold colonies will never again be a good storage risk.

4.3 Inspection Practice

Inspection procedures at buying points exert a great deal of influence over subsequent storability. At country elevators and on farms, Official inspections are not used to establish the quality of grain put into storage. Country elevators often choose not to measure factors closely related to storability--foreign material and damage. Testing causes delays in receiving, and generally, the average quality delivered to country markets is better than minimum requirements. It is easier and faster to treat all sellers alike than to make detailed analyses and discriminate.

From a storage viewpoint, lack of testing introduces uncertainty about storage risk. For example, corn at harvest normally contains about 2% or less damaged kernels (USDA, 1987a). Unusual conditions that would cause 4% damage instead of 2% would have no affect on the price paid to a grower, but would have a marked effect on the risk borne by a warehouseman guaranteeing ultimate delivery of No. 2 yellow corn, maximum 5.0% damage.

Moisture-meter errors are especially relevant to storage risk. Commercial meters generally read equal to or higher than the accepted oven standard (Hurburgh et al., 1985). High readings are not the problem for storage, low readings are. Portable on-farm units are more likely to have low-reading errors (Hurburgh et al., 1986), in some instances up to 2 percentage points lower than the oven. A more rigorous and uniform program for maintaining moisture meter accuracy (standardization) is needed. Farmers in particular need to check their meters against standardized commercial units.

Accurate inspection of in-storage grain is difficult. Without costly deep probing equipment, there is no way to completely check grain in large bulks. The equipment is almost never available on farms. Some warehouses have it; most do not. Temperature cables (again, rarely used on farms) give some indication of quality, through detection of heat rises. Cables will not indicate the actual damage level of grain. Samples can be taken during turning of grain if the grain is in a structure that can be turned. Turning is a costly way to obtain samples, however.

Government regulations require that warehouses and on-farm sealed storages (sealed under government loan) be inspected for quality and quantity. This is done two times per year by either a State or Federal warehouse inspector, depending on what agency has issued the warehouse license. Unfortunately the warehouse inspector is usually limited to a top surface examination -- totally inadequate to establish the quality of grain in storage. No amount of warehouse inspection can compensate for poor storage risk in the grain stored.

4.4. Transportation

The long-distance transportation requirements to meet the expansion of world markets have increased storage problems dramatically. A barge shipment from Iowa to the Gulf of Mexico takes 2-3 weeks; ocean voyages take up to 50 days, not including port delays in unloading. Grain intransit cannot be aerated, so grain put aboard must be able to maintain its quality without aeration.

Several studies have proved that grain is not always loaded in a shippable condition. Purdue University researchers documented increases in damage during barge shipments from southern Indiana to the Gulf (DeHoff et al., 1984). Steady heating occurred in a corn shipment to Japan even though the average moisture content was 14.5% and less (Hill et al., 1985). Yet shipments of higher moisture often do reach destination in condition. The explanation is that the current set of grade factors do not adequately indicate remaining storage life. Events far removed from the point of shipment loading, undetectable at the time of inspection, guarantee that some lots will have deterioration while others will not. Trying to accommodate the greater flexibility possible in short-haul domestic trades and the strict quality control required for world distribution in one grading system requires the export customer to write specifications in addition to or different than those for general domestic commerce. Additional tests such as moisture variation and breakage susceptibility would provide opportunities for contractual solutions to intransit quality loss.

5. EXTERNAL FACTORS AFFECTING STORAGE LOSSES

There are several factors external to grain quality and the grading system that bear directly on the U.S. ability to store high-quality grain.

5.1. Conversion From a Merchandising Market to a Storage Market

Grain storage capacity grew rapidly in the 1970's. Facilities were designed to hold grain for relatively short periods. The emphasis was on merchandising volume, so storages were set up to contain large bulks of undifferentiated commodities.

As surpluses mounted, grain was stored longer, in facilities that were not well suited for long-term quality control. Furthermore, recent new storage has been constructed in response to what is perceived as a short-lived government program. The objective in this situation is to invest as little capital and operating expense as possible in the storage. As long as the usually-traded grades provide an opportunity to "blend off" deterioration caused by imperfect storage conditions, that objective will not change.

Many grain handlers contend that spout line size is proportional to bin diameter. If this is so, then spout line problems are far greater for commercial handlers than for farmers.

Commercial handlers store in larger bins, which are usually set up for low airflow aeration rather than high airflow drying. Airflow distribution for aerating dry grain is much more critical at 0.05-0.1 cfm/bu than at 0.5-1.0 cfm/bu.

5.2. Harvesting Operations

Of the three grains covered in the OTA study, corn has the highest moisture at harvest. Growers face often conflicting incentives concerning harvest moisture content. Clearly, lower harvest moisture means less drying expense. Genetics have relieved much of the field-loss problem (from dropped ears), so delaying harvest to allow field drying can be profitable. On the other hand, growers close to central markets or large facilities are sometimes offered a high cash basis premium to harvest corn early, before the large rush hits the market. Rapid drying of corn up to 30% moisture may result; this is a product totally unsuited for export shipment because it is breakage prone and non-uniform in moisture distribution within kernels.

For a variety of reasons, corn is often held in wet storage before drying. This may be overnight on a farm wagon or for several days at an elevator. Heating almost always occurs in stored wet corn. Corn held for one day at 26% moisture in unaerated storage will loose up to one-fourth of its Allowable Storage Time. Future problems are guaranteed. Management immediately after harvest is responsible for the many differences in storage life of supposedly good-quality grain.

These issues can be resolved by 1) a genetic emphasis on drydown, 2) attention to management of wet grain (e.g., no unnecessary storage), and 3) utilization of drying systems that do not need a great deal of wet holding. Grades and Standards have little impact on the wet-grain management operations immediately after harvest.

5.3. Government Program Incentives

Government programs are creating an incentive to store grain, beyond that normally conveyed through futures pricing. The details of farm programs are given elsewhere in this study. In general, U.S. farm programs have 1) encouraged production beyond consumption and 2) made the storage of the physical commodity a necessity to receive benefits. Storage programs provide payments for up to 3 years, often negating the first in -- first out grain management philosophy necessary to counteract the exponential growth curves of storage pests.

The preceding sections have established that all quality changes occurring in storage are negative and that all grain users are affected adversely by in-storage deterioration. The policy section of the OTA study shows the possible extent to which program-induced storage has affected quality.

6. NEW TECHNOLOGIES AND RESEARCH
AREAS OF IMPORTANCE TO
GRAIN STORAGE

The next sections list new technologies and research topic areas that are important to controlling quality losses in storage.

6.1. Aeration Management Equipment

Microprocessor-based control systems have been developed for aeration. These systems monitor ambient air conditions, grain temperatures, and storage history. Their purpose is to optimize fan operation time for maximum quality control at minimum cost. There are two areas of development for these systems -- 1) the equipment (controllers, chips, cables, etc.) and 2) the control-program logic. The program logic is the crucial component, and the one needing research. Generally, this logic is considered proprietary information. Minimizing cost is a narrow balance between spoilage risk and economics. Effective calculation of when to aerate and when not to aerate is critical; otherwise, the controller can do more harm than good. Some users report significant reductions in aeration cost (energy and management time) from using controllers. However, personal discussions with others reveal distrust of the logic used to determine operation time. The technology is new enough that objective analyses are not yet published in scientific literature.

The controller is essentially a data-storage device, retaining information on previous temperatures and relative humidities. Stand-alone units mounted on bins do not have the memory capability to store needed data. There is great opportunity to connect these units with temperature cable systems and computers, especially for commercial warehouses. However, the controller seems to be more of a management optimize than a quality controller. It could prevent lax managers from spoiling grain, but it will not make better grain for good managers.

6.2. Cleaning

Cleaning is an effective way to extend storage life. Development of high-speed inexpensive cleaning systems would be beneficial, especially in market conditions favoring storage. Basic research is needed to more fully establish the storage value of cleaning. The microbiological parameters of clean grain versus uncleaned grain are not fully known, nor are the effects of density-cleaning (aspiration) relative to size cleaning (screening). For a more in-depth discussion of cleaning, see Hurburgh (1987c).

6.3. Objective Damage Determination

Damage is a subjective measurement. Recent reports indicate that digital optics are capable of identifying, not only the traditional discolored kernels, but also cracked grains as well (Gunsarekan et al., 1986). A rapid, objective test for damage would improve inspection capabilities and more importantly would permit accurate monitoring of in-storage grain quality. Damage analysis is discussed in more detail in Hurburgh (1987b). As-yet-unidentified technologies that could identify mold species would probably be the greatest benefit to storage because, through mold species, storage history can be established.

6.4. Moisture Content Variability.

Variation in moisture content among kernels is an important storage parameter. It has been measured by conductance (Pomeranz and Czuchajowska, 1986) and capacitance (as yet unpublished) to approximately ± 1 percentage point. There is one conductance-based instrument being readied for the American market.

Research needs include the identification of other methods (e.g., microwave absorption) that could measure kernel moisture more accurately and the interpretation of single-kernel moisture data at various points in the market. Moisture-content measurement is covered extensively in Hurburgh (1987b).

6.5. Impact and Cost of New Storage Technology

There is no lack of storage technology per se. Aerated upright storages are capable of maintaining quality within reasonable limits. The weaknesses are in market application of standards, lack of knowledge relative to benefits of quality control, incentives to store grain as a requirement for income support and incomplete data on storage-related grain properties.

It is beyond the scope of this paper to project the costs and benefits of tighter damage standards. Cleaning can generate 1-2 cents per bu. net profits in a storage-based operation for corn (Hurburgh, 1985). On the 6 billion bushels the USA now has in storage, cleaning could have netted the storing warehouses $60-120 million. Some warehousemen have captured this gain, but their grain will ultimately be blended with grain from handlers who did not.

Equipping the 10,000 U.S. grain inspection points (Official and house inspections) with a single-kernel meter estimated to cost $1,500 would cost about $15 million. In addition moisture-blending opportunities would be reduced. How much is very difficult to assess. A conservative estimate might be that 1 billion bushels of corn would be dried another 2 percentage points, at about 2 cents per point, for a total cost of $20 million annually. The offsetting gains in reduced mold shrink and customer satisfaction are impossible to estimate.

However, the maximum value increase from lower damaged-kernel counts can be approximated. The average percentage of damaged kernels in U.S. exports has risen about 1.0 percentage point for corn and 1.0 point for soybeans since 1984 (USDA, 1986a,b; USDA, 1987a,b). This is probably due to the longer storage times created by government farm program incentives. The usual market discounts for damage are 2 cents per point over (5.0%) and 3 cents per point (over 2.0%) for corn and soybeans, respectively. While export grain does not exceed the grade limits, it is reasonable to assume that a percentage of damage below the grade limit is no less detrimental than a percentage of damage above the grade limit. Therefore, a reduction in damage, even if below the maximum limits, should result in a higher value product received. USDA statistics report that 1525 million bushels of corn and 760 million bushels of soybeans were exported in the marketing year 1986-87. Therefore, the maximum-value gain, which competitive pressures may or may not allow the USA to capture, from better storage or less storage is about $30 million for corn and $23 million for soybeans. This assumes a reduction of 1 percentage point in damage, back to levels existing before the rapid buildup in carryover stocks.

6.6. Biological Parameters Affecting Storage Losses

There is considerable storage research that is as yet unpublished. Purdue researchers have indicated that several grain properties are altered by high temperature drying. The same observation has been made for insect invasion. Certain corn hybrids have been reported more susceptible to mold invasion than others. Much important biological research lies either unpublished or unfinished. It would be a great loss to leave these potentially significant findings in obscurity, not being applied or built upon. Modification of grain properties is a logical focus of genetic manipulation. Clearer interpretation, and more universal circulation, of current knowledge would help to focus biotechnological research on these areas of great economic significance.

7. SUMMARY AND CONCLUSIONS

Grain storage practice has a significant effect on the quality of corn and soybeans received by an enduser. Quality changes in storages are always negative, and are generally caused by increased damage levels. The following general summary is offered:

1. The conditions causing storage deterioration are well known. Corn moisture contents of 15% and greater are not safe for shipment to warm climates. Soybean moisture contents of 13.0% and greater are not safe for warm weather shipment.
2. Clean, unbroken grain is much more resistant to deterioration than grain containing the levels of broken grain and foreign matter allowed in current Grade Standards. Clean grain is also easier to manage in storage. Two conditions must be met to increase the amount of clean grain in market channels -- an economic incentive to clean and a reduction in breakage susceptibility.
3. Storage history cannot be determined by the current grade factors, but is a crucial factor in predicting future deterioration. Kernel moisture variation and breakage susceptibility would be helpful additional factors.

4. Kernel-to-kernel moisture variation has great potential to aid storage decisions. However, the correct interpretation of single-kernel moisture data will require further study.
5. There are several areas of research and developing technology--cleaning, single-kernel moisture, aeration control--that could reduce the incidence of storage loss. In general, grain properties rather than storage technology hold the greatest promise for controlling storage loss. Tighter standards for several defect-related properties would appear to be an efficient and direct method of reducing storage loss. However, storage loss will never be eliminated, and it will be minimized only when the USA is storing the minimum amount necessary for marketing and consistent distribution.

Prevention of storage loss is a defensive activity. Certain changes to correct other quality problems (infestation, foreign material, moisture variations) will improve stored grain management. Only moderate private and public resources, will assure that quality complaints do not arise from storage-related deterioration.

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Background Paper No. 5

Cleaning and Blending of Corn and Soybeans

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This background paper was prepared for the assessment "Enhancing the Quality of U.S. Grain for International Trade." The views expressed are those of the author(s) and not necessarily those of OTA.

Cleaning and Blending
of
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1. INTRODUCTION

Cleaning and blending are operations at the heart of many grain-quality controversies. They are also crucial to any effort to improve U.S. grain quality. Cleaning is usually done to control the percentage of one or more characteristics related to particle size. Blending is done to assure that grain lots are uniformly as close to the contract or specification limits as possible. Cleaning and blending often function together because particle-size factors are the ones most often approaching limits in export shipments (USDA, 1987a,b). Target percentages can be reached more accurately by cleaning and reblending the cleanings than by blending two streams of different particle size composition.

Concerns about cleaning and reblending, particularly in corn, initiated the Grain Quality Improvement Act of 1986. In essence, many people felt that there was something inherently wrong about reintroducing material that was removed and known to be of lesser value than the grain. Their concerns are underscored by the predominance of foreign material as a source of buyer complaints. In 1987, Federal Grain Inspection Service (FGIS) reported 59 overseas complaints, 30 of them related to foreign material. The percentage of broken kernels in coarse grains increases with handling, virtually assuring that a buyer will receive a greater percentage of small particles than was listed on the export certificate. Breakage compounds the continual problem of segregation in vessel holds--the fine particles remaining under the spout. When shipments start at or near the maximum percentages of small particles before handling, customer dissatisfaction is inevitable.

Both cleaning and blending can be quality-control operations, however. This paper presents the grain-quality ramifications of both operations, for corn and soybeans. The general objectives are to summarize current practice and to present the quality-improvement potential of each.

2. PRINCIPLES OF CLEANING

There are two common methods for cleaning bulk grain--screening (particle-size separation) and aspiration (density separation). Other methods are used in specialized situations. For example, gravity tables (seed weight separation) and length graders (seed size separation) are used extensively in seed-conditioning plants. However, screens and aspirators are the only methods with the throughput capacity needed for modern bulk handling. Most seed-cleaning operations are limited to 1000 bushels per hour or less; bulk grain handling, even on farms, is rarely done at less than 2000 bushels per hour. Cleaning at flow rates more than 15,000 bushels per hour is typical at commercial elevators.

Cleaner performance is usually listed as percentage points of material removed at a given throughput or as efficiency, percentage of removable material that actually was removed. This reflects the usual desire in the USA to use cleaners to reach grade limit targets, not to obtain clean grain. Thus, efficiencies substantially less than 100% are acceptable, or even desired. Cleaning is more often a merchandising operation, rather than a quality-control operation. This statement is particularly true for cleaning at commercial elevators. The rapid expansion of long-term storage has caused some reevaluation of the role of cleaning, however. Favorable experiences with low-cost storage, such as those reported by Twomey (1987) and Gilbert (1987), have pointed out both the value of cleaning as a grain management operation and the potential profitability of cleaning outside traditional merchandising objectives.

2.1. Particle-Size Separation.

The Standards for corn and soybeans use particle size to discriminate between "whole" seeds and brokens or foreign material. In corn, broken corn-foreign material (BCFM) is defined as material passing through a 12/64-inch round-hole screen, plus any nongrain material remaining atop the 12/64-inch screen (USDA, 1980a). Recent regulation defined the foreign material (FM) fraction as that passing through a 6/64-inch screen plus the nongrain material. BCFM continues to be the Official grade-determining factor, however. Formal separation of BC and FM was endorsed by the Grain Quality Workshops (NAEGA, 1986) pending completion of an economic impact study. In the workshop report, an 8/64-inch screen was suggested as an FM definition.

Soybean Grades have always had two particle-size factors, splits (broken beans) and foreign material. Soybean FM is material passing through an 8/64-inch screen plus nongrain material remaining atop the FM screen. Splits are beans or pieces of beans not passing the 8/64-inch screen but with 25% or more of the bean broken off (USDA, 1980b). Splits cannot be measured directly by screening; a 10/64 x 3/4-inch slot sieve is used as an aid to separating splits, but the inspector must hand sort both the material passing the slot sieve and that remaining atop it to isolate all split beans. Any nongrain material passing the slot sieve must be put with the FM. Thus, there is no mechanical means for managing both particle size factors in soybeans. There has been little need to address this potential operational problem because soybeans rarely contain enough splits to approach grade limits (Hurburgh et al., 1988; USDA, 1987b). Foreign material, not splits, has been the source of customer complaints.

The use of particle size as a quality criterion presumes that smaller particles are less valuable then larger ones. This assumption will be discussed in later sections. Practicality probably was a major reason for FM being determined by size. Whatever the screen size, material passing will be a mixture of broken grain and nongrain materials. The FM screen size should be set at the point where the broken grain become markedly less valuable and where nearly all true foreign matter will be removed.

Screen cleaners tumble or vibrate grain over a cleaning surface. If the screen mesh is larger than the grain, the cleaner is scalping, removing larger-than-grain particles. All material removed in scalping will be FM, nongrain material. If the mesh is smaller than the grain, it is screening--removing smaller particles--which will be a mixture of broken grains and nongrain material. Quinn (1987) summarized screen cleaner performance parameters as being throughput, screen area, percentage of material to be removed, and moisture content. A crucial point is that screen cleaner efficiency is markedly less for "near-fit" particles, close in size to the openings, than for particles much smaller than the openings. A theoretical analysis of cleaner operation is presented by Henderson and Perry (1965). There are no rigorous performance indexes or rating criteria for cleaners, a scientific deficiency that will need to be corrected if market practice ever promotes extensive cleaning of coarse grains. Figure 2-1 shows a typical screen-scalp cleaner.

2.2. Density Separation

Density separation is done by aspiration, the drawing of high-velocity air across a flowing grain stream. Particles with a lower terminal velocity will be drawn out of the grain stream. Density and surface-drag coefficient are the key factors determining terminal velocity (Henderson and Perry, 1965). The preciseness with which the air velocity and grain flow can be controlled determine the sensitivity of separation in an aspirator cleaner (Kice, 1985).

Aspirators (Figure 2-2) have fewer moving parts than screen cleaners. Cascading and multiple exposures to airflow can produce capacities up to 40,000 bushels per hour. Aspiration of corn produces a variety of particle sizes. Table 2-1, from Yang (1987), gives the particle-size distribution and percentage efficiency, relative to screening, for a Kice laboratory multipass aspirator. It was clear that, to achieve a 90% or better separation of small size particles, a significant quantity of larger particles would also be removed. The coefficient of variation (CV) among replicate tests was about 10%, probably adequate for production cleaning, but not acceptable for inspection. The Carter Dockage Tester used in Official inspections has a CV of about 3% (standard deviation of 0.1%) on No. 2 Corn (Hurburgh, 1980).

The question of whether density or size best describes undesirable material has not been adequately addressed. Corn screenings are priced by density (test weight), with 40 lb/bu or more considered acceptable. On the surface, this would suggest that density is a good criterion of value. However, density decreases with particle size (Hill et al., 1981b; Yang, 1987). Thus the discount for density in screenings may be an attempt to exclude the smaller particle sizes that are more likely to contain inert material (Hill et al., 1981b). Aspiration cleaning will produce cleanings of lower density than screen cleaning for the same percentage removal of material.

The use of particle size as a pricing criterion will present complications for the application of aspiration cleaning in corn and soybeans. Even assuming that the larger, low-density pieces (and kernels) are functionally inferior to the clean grain, the economic incentive will be to leave them in, given a particle-size definition of brokens and FM. Hall and Hill (1973) found that low-density whole kernels are not of inferior feed value, but recent studies (Paulsen and Hill, 1985) show that they are a detriment to dry-milling operations. Huff and Hagler (1985) reported that mycotoxin-contaminated corn kernels could be separated by density methods. A combination of heavy aspiration and low-capacity reclaim screening might resolve this dilemma.

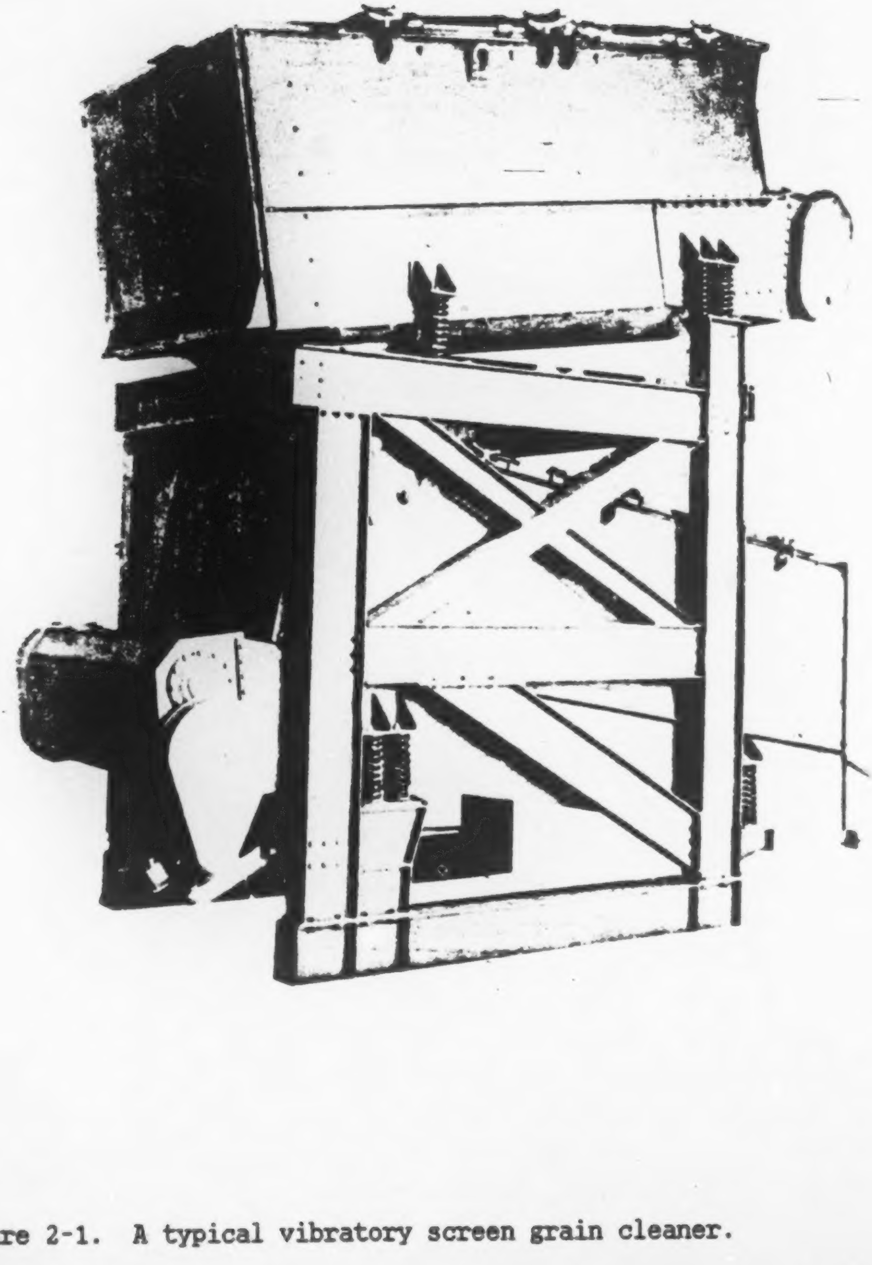

Figure 2-1. A typical vibratory screen grain cleaner.

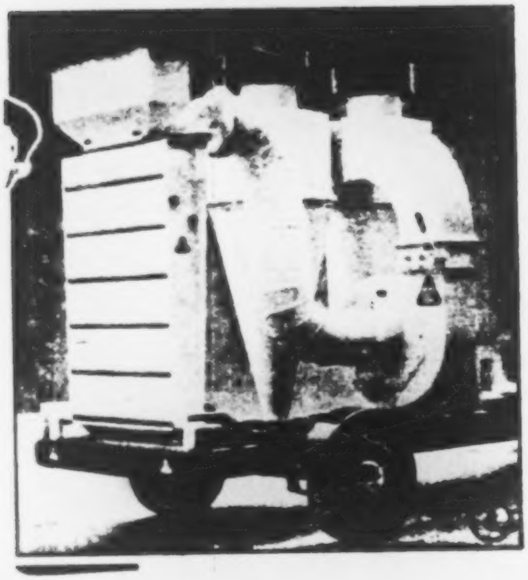

Figure 2-2. An aspiration grain cleaner.

	Percent removal of aspiration liftings, and efficiency,[a] by particle size, in 64th inch[a]							
	Corn			-----Broken corn----			--------FM-------	
Airflow, m^3/min	Above 16	14-16	12-14	10-12	8-10	6-8	4.5-6	Below 4.5
4.0	5.2 (7)	2.5 (38)	4.0 (76)	3.0 (84)	2.0 (100)	1.0 (100)	0.6 (100)	1.0 (100)
2.9	0.0 ---	0.3 (5)	0.8 (15)	1.3 (37)	1.0 (50)	0.7 (67)	0.5 (83)	1.0 (100)
Size distribution of uncleaned corn	80.0	6.6	5.2	3.6	2.0	1.0	0.6	1.0

[a]Percent efficiency of removal in parentheses.

Table 2-1. Performance of a Kice laboratory aspirator in corn. After Yang (1987).

2.3. Cleaning Practice

2.3.1. On-farm

On-farm cleaning is generally limited to corn. Several companies manufacture rotary cleaners in the 1000 to 3000-bushel-per-hour range. Most are capable of one scalp separation and one screen separation, as shown in Figure 2-3. The most common screen size for the screen separation is 1/4-inch or 3/16-inch square-mesh hardware cloth. A 12/64-inch circle will inscribe in the 3/16 square opening, so both sizes remove more than just BCFM-sized particles. Farmers with cleaners are usually equipped to feed the cleanings immediately to livestock so that the loss in weight is recovered. For centralized farm-handling systems, gravity-type screen-scalp cleaners are available. The grain cascades over several sections of perforated metal. Gravity cleaners have the advantage of no moving parts and high-throughput capacity. However, the size removal efficiency decreases with increasing throughput.

Cleaning is done on farms to improve dryer efficiency and prevent storage problems. Numerous studies have reported that freshly harvested corn rarely approaches the 3.0% BCFM limit of No. 2 corn (Hurburgh and Moechnig, 1984; Hurburgh et al., 1984; Kline, 1972). FGIS has recently reported that 34% of corn lots Officially inspected at interior points graded No. 1 (USDA, 1987a).

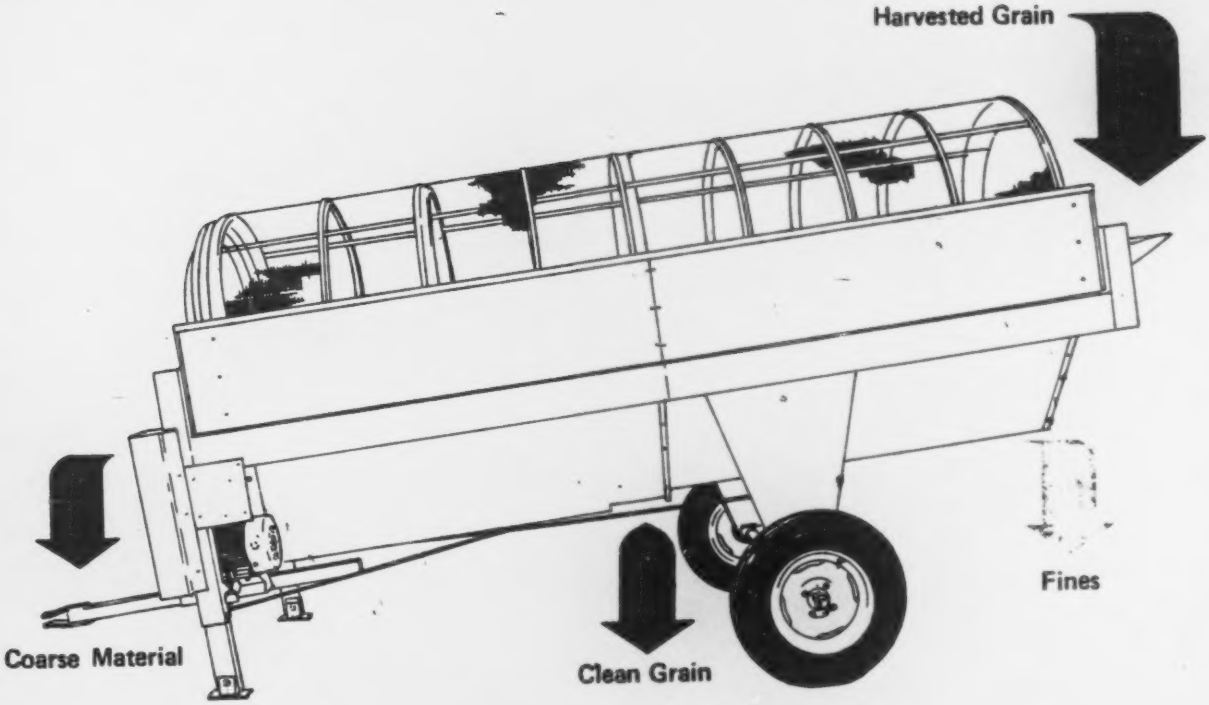
Harvested Grain
Coarse Material
Clean Grain
Fines

Figure 2-3. A rotary on-farm screen cleaner.

Therefore, on-farm cleaning is not being done to meet market grade. The operational benefits of corn cleaning will be detailed in a later section. The key point is that those farmers who do clean have perceived the benefits whereas commercial grain handlers facing the same storage and drying problems as farmers have not.

Precleaning of grain before drying is done solely to increase dryer performance. The benefits of precleaning are greatest for drying systems dependent on airflow rather than high temperature (Grama et al., 1984; Bakker-Arkema, 1988). Farm systems are of more airflow-dependent design than commercial systems. Nationally, about 80% of corn is dried on-farm, which means that there is opportunity to increase the frequency of precleaning. Precleaning will remove about 1-1.5% of corn weight, so it is not an answer to the high levels of BCFM found in U.S. export shipments. Precleaning also requires immediate disposal of wet fines that are extremely susceptible to spoilage.

Soybeans are typically harvested with FM levels below 1% (No. 1 soybeans) (USDA, 1987b; Hurburgh et al., 1988). They are not usually dried. Therefore, there is little current incentive for on-farm cleaning of soybeans.

2.3.2. In commercial channels.

Corn and soybeans are cleaned in commercial channels to stay within grade limits. Cleaning to make grade is done at loadout, rather than at receiving. Complete cleaning is not desired; only that necessary to bring the grain within limits. In the USA, precleaning at receiving is rare; this contrasts with European practices reported by Bakker-Arkema (1988).

Commercial cleaning requires high flow rates. Gravity or vibratory screen cleaners are usually used, with capacities up to 40,000 bushels per hour for 1-2 percentage points removal. Scalping can be done with vibratory units or with drag scalpers, inclined perforated beds with holes large enough to pass grain but not large pieces.

There are three general configurations of cleaning systems in elevators. 1) The entire grain stream can be passed over the cleaner bed, with the throughput adjusted to produce the desired amount of broken grain and foreign material in the cleaned product. Alternatively, the stream can be overcleaned, and the cleanings metered back as required to reach the target percentages. This procedure is still legal so long as the cleanings cannot be classified as 100% foreign material or dockage by the Official definitions of those factors. Corn BCFM can be reblended as desired by the elevator. 2) The entire stream can be cleaned over a screen larger than the size definition for the targeted factor.

The coarse cleanings are either recleaned to remove the smaller size material or reblended directly. The second option is particularly useful for cleaning soybeans because it allows the elevator to use corn screens for cleaning soybeans. 3) The stream can be divided so that part is cleaned and part uncleaned. The division proportions control the quality of the final product.

All the designs are useful only if part or all of the grain on hand exceeds the limits for BCFM (corn) or FM (soybeans). This may not occur at the first point of sale--the country elevator. Studies of handling breakage indicate that about 0.5% BCFM is created per elevation in commercial channels, given "average" breakage susceptibility. Depending on drying method and handling equipment, breakage in farm handling systems varies widely. Given 1-2% BCFM in corn leaving the farm, the first handler may not need to clean corn. As discussed earlier, farmer-delivered soybeans usually are below grade limit for FM, again lessening the need for the country elevator to clean. The point is that increased incentives for cleaning will not be met by simply doing more cleaning on farms and at country elevators, even though the interior is the most favorable location for utilizing the cleanings. Interior cleaning will remove the majority of inert material--stems, pods, cobs, dirt, etc. so that further cleanings will be almost exclusively broken grain in some form.

2.3.3. Discount practices

Interior discounting practices determine the extent of cleaning before grain reaches export terminals. Corn is usually priced to the farmer basis No. 2 standards, 3.0% BCFM, with a discount of about 2 cents per bushel per point over 3.0%. The proportion of No. 3 grades (4.0% BCFM) increases through the market chain to about 75% at export (USDA, 1987a). The two cent discount is greater than the value of whole corn. Above 3.0% or 4.0%, the BCFM is ostensibly valueless. This contradicts the findings of Hill et al. (1981a) that the feed value of screenings is nearly equal to that of corn. The market price of BCFM screenings, 40 lb/bu or greater, is 50-80% of whole corn (Brooks, 1978). The apparent discrepancy can be explained by concluding that two cents per bushel is the approximate cost for a single handler to clean corn, assuming that the handler generates about 1% BCFM in receiving and loadout.

Export grain must meet grade limits, or it will not be put aboard ship. Therefore the market discounts reflect the cost at which an exporter will have equal preference for cleaning at the export terminal or cleaning at the interior origination point. The exporter's cost will be cleaning plus freight cost to move cleanings into position for use.

Soybeans are priced in the interior basis U.S. No. 1 Standards, 1.0% FM. In the period 1984-1986, 67% of U.S. export soybean cargoes were U.S. No.2 (2.0% FM) (USDA, 1987b). Some export customers have established individual contract terms relative to soybean FM. Taiwan buys maximum 1.5% FM, by sublot (cu-sum not to apply). Japan buys maximum 2.0% but assesses a discount above 1.0% (Huffman, 1987). The usual interior discount for FM is a one for one percentage deduction, which in essence is no discount at all if the FM is truly FM, not broken soybeans. The one for one discount falls most heavily on handlers experiencing breakage of whole or split beans into FM.

3. EFFECTS OF CLEANING ON GRAIN QUALITY

Cleaning is intended to remove material that is of lower value than the remaining grain. The Standards should adhere to the purposes established in the Grain Quality Improvement Act. Therefore, the particle-size definitions and grade limits should correspond to changes in value. The next sections examine the degree to which the current and proposed corn and soybean Standards meet that criterion.

3.1. Size Separation of Corn

3.1.1. Distribution of particle sizes in market channels

Several studies have measured the relative concentration of various fines sizes in market corn. These data are summarized in Table 3-1. It is important to remember that the data in Table 3-1 do not account for any cleaning that may have been done by previous handlers. The percentage passing through a 12/64-inch round-hole screen, the current BCFM screen, is the reference base. Amounts passing through other screen sizes are expressed as percentages of the weight passing through the 12/64-inch screen. In this way, the amount of screenings that would be removed with alternative FM Standards can be related to current cleaning practices. As an example, about 37% of what is now BCFM will pass through an 8/64-inch screen (the soybean FM screen). The remaining 63% will fall between 12/64 inch and 8/64 inch. A smooth curve fitted through the "averages" data yields an equation:

$$(3\text{-}1) \quad P_i = e^{(0.2625s + 1.455)}$$

where:

P_i = weight passing through the i^{th} screen as a percentage of weight passing through the 12/64-inch screen

s = hole diameter of the i^{th} screen

The relative concentrations of various particle sizes did not change appreciably through the market and were independent of BCFM concentration. This statement seems contradictory to Hill's consistent findings of more small fines at export unloading and at export end-user. However, the data in Table 3-1 stop at export-certificate sampling; only handling within the United States is included. A relative increase in smaller fines after export certification suggests that handling during vessel loading, vessel unloading, and importer distribution is rougher than the usual domestic handlings. Extension of this logic would say that many export quality problems related to fines and dust are created after the final inspection and therefore will not be completely solved by policies that encourage more domestic cleaning of grain unless coupled with programs to reduce breakage susceptibility.

Reference	Data Source	Number of lots	Weight passing through screens, as a percent of weight passing through 12/64" screen										Percent passing 12/64	Percent coarse FM[a]
			16/64	15/64	14/64	12/64	10/64	8.5/64	8/64	6/64	4.5/64	3/64		
Hill et.al (1979)	Export Shipments 1974-75	5	246.5			100.0		44.4		21.5		6.4	3.20	
Iowa Dev. Comm. (1977)	Country elev. recpts,1975 IA	345		301.6		100.0			41.9				1.24	.20
	Country elev. recpts,1976 IA	444		259.8		100.0			39.0				1.64	.12
	Country elev. shpmts,1975 IA	249		267.2		100.0			31.2				1.89	.16
	Country elev. shpmts,1976 IA	374		256.1		100.0			37.1				2.05	.15
	River terminal recpts,1975 IA	131		285.5		100.0			34.8				1.32	.12
	River terminal recpts, 1976 IA	150		278.6		100.0			35.7				1.54	.13
	River terminal shpmts,1975 IA	17		282.9		100.0			39.4				1.75	1.02
	River terminal shpmts,1976 IA	20		265.4		100.0			52.9				2.40	.81
	Export recpts by barge, 1975	4		237.6		100.0			41.7				2.71	.28
	Export recpts by barge, 1976	5		229.2		100.0			40.9				3.08	.22
	Export recpts by unit train,1976	38		255.1		100.0			31.4				2.74	.16
	Export shipments 1975	3		240.7		100.0			36.2				3.12	.22
	Export shipments 1976	3		230.0		100.0			39.9				3.33	.27
Hill et al. (1981a)	Country elev. recpts,76-77 IL	290		247.4		100.0	54.3		34.2	19.2	12.3		1.14	
	Country elev. shpmts,76-77 IL	290		211.9		100.0	58.3		31.9	17.8	11.4		1.85	
	Terminal receipts 1976-77 IL	250		196.5		100.0	63.1		36.0	20.5	13.1		2.00	
	Terminal shipmts 1976-77 IL	250		181.5		100.0	64.6		36.9	19.6	12.3		2.60	
Hill et al. (1981b)	Export shipments, 1978-79	10				100.0			33.3		12.1		3.30	
Grams et al. (1984)	Country elevator shpments 1981 US	16	243.9		163.4	100.0	68.2		31.7	19.5	12.2		2.25	
Hill et al. (1985)	Export shipment sublots, 1985	8	266.9			100.0		44.1	39.3	19.9		5.3	5.32	
Hurburgh (1986)	Hopper cars at origin, 1986 IA	75	273.5		152.1	100.0	62.1		29.8	16.1			2.11	.15
	River terminal shpments, 1986 IA	17	213.6		139.9	100.0	60.7		33.4	18.5				
	Averages	2994	248.9	248.6	151.8	100.0	61.6	44.2	36.8	19.2	12.2	5.8	2.39	.29

[a] Coarse FM is nongrain remaining atop the largest screen in the study

Table 3-1. Summary of data on corn particle-size distribution.

Corn is cleaned even with present standards. Once the level of BCFM reaches the grade limit, any further breakage will represent discounts. The usual rule-of-thumb is that corn gains 0.5% BCFM with every elevation, more or less depending on breakage susceptibility. If corn is at 2% BCFM leaving the farm, then 2 elevations will take it to 3% and 4 elevations will take it to 4%. When the corn reaches the grade limit level of BCFM, it is saturated. Any more breakage will either cause discount or have to be removed. Saturation will probably occur at the country elevator, or possibly at the next terminal handler. The amount of screenings removed will be proportional to the number of handlings in a given market chain.

Fewer cleanings might be removed with separate BC and FM standards as compared with the current BCFM designation. One proposal for corn FM is to discount it one-for-one, beginning at 0.0 or 0.5%, as is done with wheat dockage (NAEGA, 1986). Presumably, nearly all the FM and enough BC to stay within grade limits would be removed through the export handling chain. Table 3-2 is an application of equation (3-1) to estimate total cleanings that would be removed with separate BC and FM Standards relative to the BCFM removed under current Standards. Increase in BCFM (12/64-inch) sized particles is used as the baseline because most handlers are accustomed to measuring BCFM changes. The choice of reference is one of convenience because the actual grain breakage is independent of standards used to describe it.

Total Increase (I) in BCFM-sized particles, %	Percent of grain weight removed (P_r) to make grade [a]					
	No. 2 Yellow Corn			No. 3 Yellow Corn		
	6/64 FM defin.	8/64 FM defin.	Current Grades	6/64 FM defin.	8/64 FM defin.	Current Grades
0	0.0 (-)	0.2 (100)	0.0 (-)	0.0 (-)	0.2 (100)	0.0 (-)
2	0.5 (60)	1.0 (100)	1.0 (19 or 37)	0.3 (100)	1.0 (100)	0.0 (-)
5	3.5 (24)	3.5 (59)	4.0 (19 or 37)	2.5 (34)	2.5 (83)	3.0 (19 or 37)
10	8.5 (12)	8.5 (46)	9.0 (19 or 37)	7.5 (24)	7.5 (52)	8.0 (19 or 37)

[a] Number in parentheses is percent share of FM in the cleanings.

Assumptions: Corn harvested with 2.0% BCFM, FM is weight-deductible starting at 0.5%, BC factor limits are the same as current BCFM limits, P_f calculated from (3-1).

Table 3-2. An estimate of the amount and composition of corn cleanings under two FM definitions and the current Grades.

The numbers in Table 3-2 were calculated from the equation:

$$(3\text{-}2)\quad P_r = (P_f(B_o + I) - G_f) + ((1.0 - \frac{P_f}{100})\,(B_o + I) - G_b)$$

where:

P_r = percent of corn weight that must be removed to make grade

P_f = relative percentage of FM in BCFM from eq. (3-1).

B_o = initial percentage of 12/64-inch particles.

I = increase in percentage of 12/64-inch particles.

G_f, G_b = grade or discount limits for FM, and BC, respectively.

with the constraint that neither $(P_f\,(B_o + I) - G_f)$ nor $((1.0 - \frac{P_f}{100})\,(B_o + I) - G_b)$ will be less than 0.0. Table 3-2 establishes two key points:

1. Given an increase in breakage of 5% or more (approximately 10 elevations), the choice of FM screen size will not affect the amount of cleanings removed. There may be less cleanings removed with separate BC and FM standards, depending on where the factor limits are set for BC.
2. The presence of a separate FM standard and the screen size selected for FM will affect the composition of cleanings removed. The two size standard will eliminate incentives to reintroduce very fine material such as dust. The efficiency curve for screen cleaners is also important

in evaluating screen sizes for FM. Assuming that at some point the corn would have to be cleaned for broken corn (as opposed to FM), this cleaning will remove nearly all the FM while only a portion of the BC. Thus, cleaning practices may not have to change greatly to accommodate a two-size corn standard.

3.1.2. Nutritive value of cleanings

Hill et al. (1981a) measured the nutritive value of various particle sizes. Their results for protein, oil, fiber, and digestible energy are given in Table 3-3. There was no particle size that discriminated by nutrient content, nor was there a dramatic reduction in nutrient content with decreasing particle size.

A feed cost analysis showed no sharp decline in value over screen size. The value of screenings depended more on the price of protein (soybean meal) relative to corn than on the size of screen. Although digestible energy was less for the smaller sizes, this loss was offset by the higher protein content to the point that, with high soybean meal prices, the small fines could have a higher value than the larger fines. Toxicity risks are greater with fines, however, than with whole grain because mold invades broken grain preferentially to whole grain.

Property	Whole corn	Size range, 64th inch					
		15-12	12-10	10-8	8-6	6-4.5	4.5->
Protein, % dry basis	10.20	10.06	10.35	10.38	10.44	10.97	12.27
Oil, % dry basis	4.47	3.86	4.25	3.40	2.48	2.43	2.43
Fiber, % dry basis	2.24	2.34	2.64	2.85	3.51	4.24	5.91
Digestible energy, Kcal/lb.	1785.80	NA	1717.30	1691.50	1660.50	1631.90	1610.80

Table 3-3. Nutritive value of corn fines, by particle size. After Hill et al. (1981a).

The dust and inert matter was concentrated in the sizes 8/64 inch and below, whereas weed seeds were mostly between 10/64 and 6/64 inch. An 8/64-inch screen would remove most of these objectionable, appearance-degrading materials.

3.1.3. Aeration and drying costs

An Iowa State University study (Grama et al., 1984) established a large effect of fines on airflow resistance and fan-power requirements. The smaller particle sizes severely restrict airflow, as shown in Table 3-4. The sharpest restrictions occur with the 8/64-inch size and smaller.

3.1.4. Storage and mold growth

The Hill et al. (1981a) study found that the smaller the particle size, the less starch was available to support mold growth. The broken corn (sizes between 16/64 inch and 8/64 inch) was much more biologically active than either of the smaller sizes under consideration for FM classification. However, several unpublished reports have indicated that the concentration of mold spores, insect larvae, etc., is much greater in particles smaller than 12/64 inch than in the whole and large broken corn.

The fines also segregate in spoutlines, causing shipment uniformity problems. Removal of segregatable particles would

	Particle size, 64th inch						
Percentage increase in airflow resistance per percentage point increase in fines	16-14	14-12	12-10	10-8	8-6	6-4.5	4.5->
	3.0	5.7	10.2	25.6	63.1	134.4	64.8

Table 3-4. Increase in airflow resistance of corn, by particle size. After Grama et al. (1984).

substantially reduce quality variability. In Hill's export quality studies, BCFM varied up to 7 percentage points in the same ship, despite the use of a cu-sum loading plan that effectively limits the range among sublot analyses to about 0.8% or less. Hall (1984) contended that material 12/64 inch and below segregated in spoutlines while the larger pieces rolled with the whole corn. Handlers often use a 10:1 rule of thumb for segregation; the spoutlines contain about 10 times more fine material than the edges.

Segregation affects aeration as well as trading uniformity. Concentrated fines have more airflow resistance than the surrounding whole corn; therefore, the air detours around them. Yet with their higher levels of mold, mold spores, and insect larvae, spoutlines need relatively more aeration to store safely. If additional fan power is used to compensate, aeration energy requirements will be much higher than would be needed for clean corn.

3.2. Size-Separation of Soybeans

Particle-size properties of soybeans have not been studied as extensively as those of corn. Increases in soybean FM during domestic handlings have not been documented. However, Hill et al. (1981b) and Nicholas and Whitten (1978) found that FM increased about 0.5% and splits 2-5%, in the handlings after final export certification. Vessel loading and unloading are among the most rigorous of handlings, so these data probably show larger increases than would be expected in domestic handlings.

Splits cause higher free fatty acid levels (Nicholas and Whitten, 1978). There are no data relating splits to any other quality factors or to processing yields. Conversations with domestic processors indicate that low moisture content (a causative factor for increased splits) is more troublesome than the splits themselves.

Soybean FM probably has the same detrimental effect on storage management as does corn FM. Until recently, however, until recently there was little market incentive to store soybeans for extended periods. Drying is not a major concern in soybeans. In-house data from one grain firm suggest that particles 8/64-inch in diameter or less (the current FM screen size) are most prone to forming spoutlines.

The nature of soybean FM changes in the market chain. The majority of FM at the farm level is inert material-pods, stems, dirt, etc. (Hurburgh et al. 1988). About half the maximum FM allowed in U.S. No. 2 soybeans is already present when the grain leaves the farm. The rest arises from breakage in handling, which means that reduction of soybean breakage susceptibility plus more rigorous on-farm cleaning would essentially remove the long standing difference in FM content of U.S. beans compared to South

American beans. The key again is to clean early, where cleanings can be used, then to maintain cleanliness through breakage control. Causative factors for soybean breakage susceptibility have not been documented as completely as for corn. The treatment of unthreshed pods deserves special mention. Current inspection procedure requires that unthreshed pods be manually shelled by the inspector, with only the pod weight counting as FM (USDA, 1980b). The pod weight is typically 10-20% of the total pod and bean weight. Unthreshed pods are a particular problem in damp years. Furthermore, the openings on typical mechanical grain probes are not large enough to consistently collect representative amounts of pods. A load containing 3-4% unthreshed pods will clog dump pit gratings spaced 2-3 inches apart. Scalping will remove the pods, but the beans will be removed also. Therefore, the grading procedure for pods cannot be mechanically reproduced in elevators, and the pods are not representatively sampled.

4. CLEANING IN THE U.S. GRAIN MARKET--INTERACTIONS

4.1. Grades and Standards

The Grades classify grain into a small number of quality categories. This is useful to maintain interchangeability of shipments, market liquidity, and commonality of terms among buyers. However, the universal use of Grade categories makes them de facto targets for quality control. FGIS data clearly show that corn BCFM and soybean FM are the factors most consistently near the grade limits in export shipments.

As long as grain is traded against a grade limit in a manner that prices grain with some FM the same as grain with none, cleaning will remain an operation of last resort, to be done only if grade cannot be met any other way. Potential cost savings from handling clean grain and consumer satisfaction from receiving clean grain will never be explored because each handler perceives his maximum profit to be from selling the highest FM allowable without discount. The General Accounting Office reported an interview with an exporter who stated that he was pleased that his elevator could come within 0.1% of the maximum on a consistent basis (GAO, 1986). For a throughput elevator that does not store grain for long periods, maximum profit is indeed realized by selling maximum FM.

4.2. Handling Rates

The higher the handling rate, the more difficult and costly cleaning will be. Export contracts contain sizable premiums for fast loading of vessels (Huffman, 1987). If exporters were forced by contract to clean more completely, either loading rates would be reduced or in-house precleaning would be done. Precleaning is most suited to small grains that are not breakage prone. In coarse grains, the extra handling(s) for cleaning would themselves generate additional breakage. It should be obvious that cleaning needs would be vastly reduced if the inherent susceptibility to breakage were reduced.

4.3. Elevator Design

Screen cleaners are bulky and generate vibrations in structures. Retrofitting would be costly unless more compact, inherently balanced designs become available. One European firm is offering a combination aspiration-centrifugal screener in the USA. This machine was designed to clean wet corn at moderate flow rates (4,000-10,000 bu/hr).

As long as cleaning is perceived to be a merchandising operation only, capacity requirements will be large. However, cleaning before and after corn dryers would require much smaller machines. Cleaning at drying makes the most sense, if, at the same time, breakage susceptibility is controlled to the point that corn once cleaned stays clean. Cleanings will also be freer of mold, and most likely more valuable, the earlier in the storage chain that they are removed.

Drying capacities of 6,000 bu/hr or less are typical of commercial elevators (Bakker-Arkema, 1988). Likewise, transferring grain to long-term storages is often done at lower rates than transfers within the workhouse of elevators. Handling operations that dry and store can utilize lesser capacity cleaning equipment than operations that solely merchandise grain, transferring it from one mode of transportation to another. The more merchandizing steps in the chain, the fewer cost-efficient cleaning opportunities will exist.

5. INCENTIVES FOR CLEANING

5.1. Under Present Standards and Incentives

Two scientists, Hill (1984) and Hurburgh (1985), have contended that cleaning at the 12/64-inch level or less could provide net profit to certain types of operations. Hall analyzed a throughput export operation, Hurburgh a storage-based country elevator operation. Profit potential was clearer at the country elevator. Benefits arise from several sources.

In corn, small pieces 12/64-diameter and smaller cause the most increase in airflow resistance. At 3% BCFM, corn has about 2.2 times the static pressure resistance that it would if it were clean. The finer the particles, the more increase there is in airflow resistance. Figure 5-1 shows the multiplier (k) factor for uncleaned corn, for corn with all the BCFM percentage. Three lines are given; for uncleaned corn, for corn with all the BCFM (12 to 64-inch and below) removed, and for corn with all the FM (8/64-inch definition) removed. Figure 5-1 was generated from a combination of the average particle-size distribution data (Table 3-1) and airflow resistance properties (Table 3-4).

A decrease in static pressure, generated by cleaning, will increase fan output airflow, the actual amount of increase being dependent on the slope of the fan output curve. The "flatter" the output curve, the more sensitive fan output is to changes in pressure. Fans differ, but as an example, an airflow increase of 5-10% per inch of water reduction in static pressure would be average for 10-hp centrifugal fans (MWPS, 1980). Increased airflow means shorter storage operating time and less cost. Hurburgh (1987) calculated that aeration costs of about 1 cent per bushel annually could be saved by storing clean corn as opposed to No. 3 corn at 3.7-4.0% BCFM. Anderson (1973) reported actual aeration costs for 100 days of storage in 450,000-bu tanks to be 6 times greater for No. 3 corn than for naturally dried No. 1 corn.

Segregation of FM also increases aeration cost. Hurburgh (1987) presented an example of segregation in a corn storage. The center core contains about 10 times the concentration of BCFM as the majority of the bin. Aeration rates in the center are 5-10% of the bin average. To compensate, the entire bin must be overaerated, wasting energy and removing moisture that could have been sold for full value.

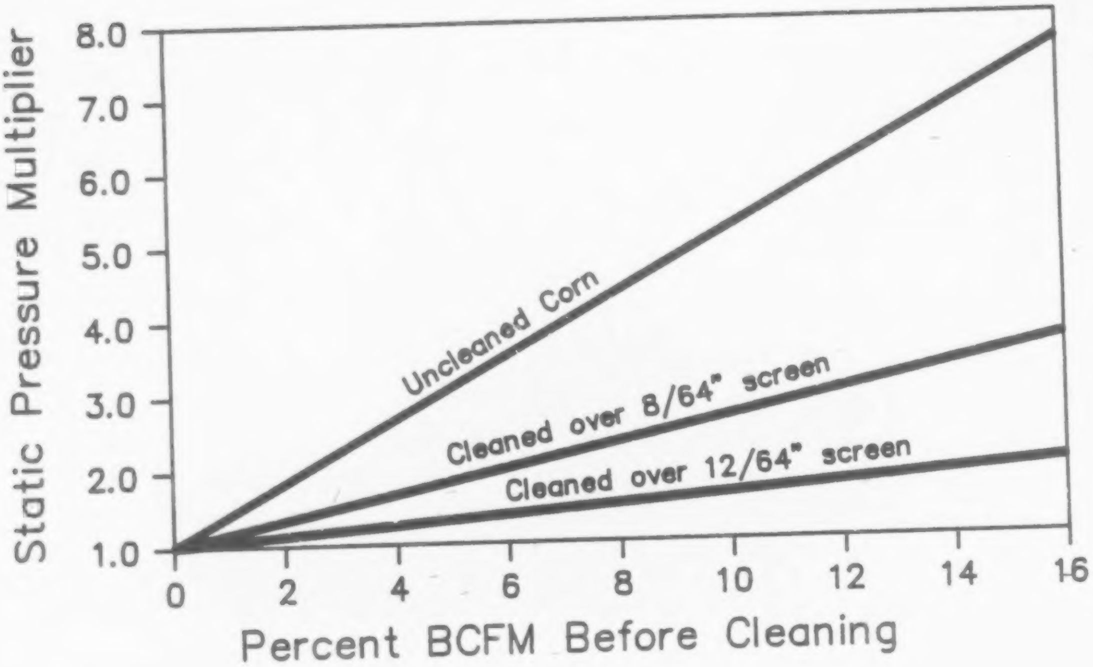

Figure 5-1. Airflow resistance multiplier factors for cleaned and uncleaned corn. Source: Hurburgh (1987).

Some moisture will inevitably be lost during routine aeration. For typical air conditions in the north-central USA, corn moisture loss can be estimated by:

(5-1) $M_1 = 0.005\ Q_b t$

where:
Q_b = airflow rate, cfm/bu
t = operating time, h
M_1 = moisture loss, lb/bu

for fall conditions and:

(5-2) $M_1 = 0.0075\ Q_b t$

for spring conditions. The difference between fall and spring arises from higher average relative humidity in the fall. Operating 2000 total hours at an average of 0.1 cfm/bu, split equally between fall and spring would give total moisture loss of 1.25 lbs/bushel and a final moisture content of 13.1% from a starting moisture of 15%. Moisture loss will stop when grain reaches ultimate summer equilibrium, 12-13% moisture. Anything that reduces fan operating time would be helpful in moisture shrink. Maintaining moisture at 14% instead of 13% would save about 1.5 cents per bushel in saleable weight per bushel. As a general rule, a two percentage point reduction in moisture content (by slow drying) will double breakage susceptibility (Dutta, 1987).

Mold growth, which can be caused by lack of aeration, will cause shrink, even if damage levels do not exceed the grade limits. For every 2-3 percentage point increase in damaged kernels, about

0.5% of the grain weight is lost (Steele et al., 1969). Therefore an increase in damage from 2% to 5% is economically significant even though no direct damage discounts will apply.

An example of costs and benefits for corn cleaning is given in Table 5-1. This is a case-study example that applies to storage-based operations. The storage benefits--less aeration, mold shrink--would not apply to throughput merchandizing operations. However, in the example, cleaning yielded a net profit even though no premium was included for the clean grain relative to normal U.S. No. 2 or No. 3 corn. Because several assumptions were used to determine cost-savings, the applicability of the conclusion must be tempered with actual data for individual situations. Clearly, the cost-savings items are subject to more uncertainty than are the expenses. Kiser (1984) reached similar conclusions in studying aspiration cleaning of wheat.

Cleaning seems in certain situations to be profitable even under present Standards. This does not mean that the Standards are providing incentives to clean, only that their disincentives can be overcome by operational gains. The expansion of case-study examples to more universal conclusions is an area of great research need, and one with a large short-term payoff. Such study and accompanying public education does not in any way depend on the success or failure of specific Standards proposals. The

	Cost savings and expense, cents/bu, for cleaning corn at:	
	12/64-inch	8/64-inch
I. Cost savings and revenues		
1. Feed value of screenings	4.5 (75%)	1.3 (60%)
2. Freight savings ($18.00/ton)	1.5	0.6
3. Aeration cost	1.5	1.2
4. Dust shrink savings (0.2%)	0.4	0.4
5. Mold, insect shrink savings (0.2%,0.1%)	0.4	0.2
6. Moisture shrink savings (0.6%)	1.6	1.6
Total savings	9.9	5.3
II. Expenses		
1. Loss of saleable weight	6.0	2.2
2. Cleaning expense	1.5	1.5
Total expenses	7.5	3.7
III. Profit, cents/bu	2.4	1.6

Assumptions: Corn value $2.00/bu, aeration rate = 1/10 cfm/bu; Corn contains 3.0% BCFM, 1.1% material under 8/64 inch; no inbound discounts levied for BCFM or 8/64-inch material, corn stored 9 months in the Western Corn Belt.

Table 5-1. An example of costs and benefits from corn cleaning.
Source: Hurburgh (1987).

utilization of improved quality as a cost-control technique is sound policy regardless of Grades and Standards.

5.2. Under Alternative Market Conditions

There have been numerous proposals to change standards relating to fines and FM. The Grain Quality workshops proposed that BC and FM be separated as two factors (NAEGA, 1986). This was an extension of similar proposals initiated nearly a decade earlier (Jackson, 1978). The American Soybean Association has consistently supported as national organization policy the creation of a "zero-based" FM standard. In essence, this means having no stated tolerance limits for FM in the Grades, allowing the market to begin discounts or set limits beginning at 0%. Wheat dockage pricing operates on the same concept.

Any standard that reduces the amount of broken grains or FM allowable without penalty will encourage more cleaning, provided the market establishes pricing practices to support the change. Uncertainty about market reaction is the reason Standards change proposals have not been more aggressively advanced. The presence of a new discount is readily evident to an individual grower or handler, whereas a potential increase in demand or overall price level is not.

No assessment of the impact of new Standards on cleaning or general demand can be made before economic-impact research is done.

This fact was recognized in the Workshop proposal on BCFM. A relatively specific impact study was described and is worthy of inclusion. Study requests are often regarded as stalling tactics; this one is not. Alteration of the U.S. Standards for cleanliness will affect every physical handling operation from farm to end user. Change may be a competitive necessity, but market participants must have some advance estimates of the potential cost-benefit distribution. Failure to quickly complete such research will prolong the debate over "dirty grain," assure that nothing will be done in the short term and give credence to critics who contend that U.S. grain handlers only wish to preserve the status quo. As evidenced by the preceding sections of this report, much of the supporting information for economic impact studies is already available. This information will not be aggregated until support from some source not limited to considering the welfare of an individual market participant causes it to be aggregated.

6. NEW TECHNOLOGIES AND RESEARCH NEEDS RELATED TO CLEANING

Most of the technology and research needs have been discussed in connection with other sections. They are summarized here.

6.1. Technologies

6.1.1. Aspiration cleaning

Aspiration cleaning is mechanically simpler and, by one account (Kiser, 1984), cheaper than screen cleaning. Although there is some lack of scientific design data, several companies will continue to advance aspiration technology as applied to grain handling. Multipass designs, where grain is aspirated several times at progressively increasing air velocities, have improved separation efficiency (Kice, 1985). Aspiration cleaning will become more prevalent if clearly demonstrated to be capable of cleaning at normal production handling rates. Aspiration has the disadvantage of separating by a different principle, density, than is used to classify material in the Grades.

6.1.2. Rotary screen separation

Several European cleaners are arranged to use centrifugal force rather than vibratory, motion, or impact to cause screen separation. The one offered on the U.S. market also has aspiration before the screens. The principle was designed to preclean wet grain before drying. With 80% of U.S. corn dried on farms, it is doubtful if a moderate capacity (4,000-10,000 bu/h) cleaner will penetrate the commercial market. However, it is a viable concept for preparation of specialty shipments and might be successfully applied to cleaning corn after commercial drying. The problem in corn cleaning is that most breakage occurs after initial receiving and drying. Any handlings after the dryer are generally high-capacity handlings (15,000 bu/h or faster). Furthermore, corn elevators generally handle soybeans also. Soybeans are rarely dried.

6.1.3. On-farm cleaning

Many of the cost-control opportunities are in on-farm cleaning. Equipment has been available--small rotary and gravity cleaners. As awareness of cleaning increases, there will be pressure to refine these machines and optimize their operation. They will need to be more precise in their separation. Users will need information on the value, marketability, and storability of cleanings to match management practices to market need. There is no estimate available on the percentage of farm-stored grain that is cleaned either before storage or before delivery.

6.1.4. Cleaner control

Rapid sensing systems for physical properties open possibilities for on-line control of cleaning systems. There are no commercial devices of this type, but investigative work is being done. The demanding separation needs of the seed industry have generated one study utilizing acoustic principles to identify sound versus damaged or nonviable seed. Digitized optics are capable of measuring particle-size distributions (Paulsen 1988).

Cleaner control would have application regardless of Standards changes. On-line response of cleaner parameters (throughput, table angle, air velocity) could be profitable whether one was cleaning to meet a target (as is done with current Standards) or to obtain the cleanest possible grain. Indeed, the more restrictive legislation becomes in controlling handling and blending practices without changing Standards, the more incentive there will be to design machines that will meet desired targets in one pass.

6.2. Research Needs

6.2.1. Economics of cleaning

Development of cost-control benefits and economic impact studies for Standards changes is essentially research on the economics of cleaning. As discussed earlier, there is great need to expand this work. Cost-control research has particularly attractive payouts because no public policy or Standards changes would be required to implement its results. An operation storing 10 million bushels of corn stands to gain $100,000 annually if cleaning will net them one cent per bushel. The exact proportions of benefit to the aggregated handling industry cannot be estimated easily; economic impact research will be needed in that area.

6.2.2. Properties and marketing of cleanings

Greater knowledge of cleanings properties, both in corn and soybeans, will lead to better utilization and more market acceptance. The aspiration versus screening question will be resolved only with accurate comparative information on cleanings properties. As noted earlier, aspiration liftings properties of corn and all cleanings properties of soybeans are not well known.

Topics of importance are:

- feed or other utilization value
- content of mold spores or mycotoxins
- storage properties
- density
- explosivity and safety
- marketing standards
- spoutline control

Biological data of this type are costly to collect and inherently highly variable. Thus, a continuing effort by several geographically distant research institutions will be needed. A total commitment of about five scientists and their support staff for about 3-5 years will be required. At $200,000 per SY, this represents $1 million per year. The work does have a finite time span; the problem is not open ended. The structure for coordination is already in place through the North Central Regional Research Project NC151, provided that participating university scientists can effectively plan and act as a group.

While the above discussion specifically applied to cleaner and cleanings research, we must not ignore the great contribution of breakage susceptibility to the need for cleaning. Breakage susceptibility research has been slow and complicated, but progress in breakage control will do more to alleviate cleaning problems than any redesign or expansion of cleaning capacity.

6.2.3. Cleaner design and performance parameters

The design of cleaners has not had to be optimized. Cleaning has been accepted as a last-resort operation. Whether for aspiration, screening or other sorting principles, basic engineering data need to be generated. The objective is to increase efficiency and throughput at reduced cost. An example would be alternative flow patterns for grain and air in aspiration cleaning.

There are no rigorous engineering standards for evaluating cleaner performance. If the market attaches more economic value to cleaning, then better descriptive indices and performance tests than "percentage points removed" will be needed. The place for this activity is in professional societies such as the American Society of Agricultural Engineers (ASAE). ASAE publishes standard design principles and tests for various agricultural equipment, including grain handling equipment (ASAE, 1988).

The implication of cleaning is control of some particle-size or foreign-material property. A more advanced concept would have other undesirable properties sorted out of grain--for example, mold-damaged kernels, or kernels with internal insect infestation. A combination of properties data, machine design and high-technology sensing will be needed to fully develop these possibilities. Fruits and vegetables are routinely sorted by colorimetric methods. Low-density undesirable nuts are sorted from flow streams. These products are of higher value and are more sortable than grains, but potential grain-sorting concepts have not been well developed. Joint ventures between public research institutions and technology firms are most likely to provide a balance of basic science and product design for this work.

7. PRINCIPLES OF BLENDING

7.1. Purposes for Blending

Blending is a much maligned operation that occurs at every point where grain is moved. Technically, any transfer that produces a combination of kernels not previously mixed is blending; for example, harvesting or drying. However, for this paper, blending is the deliberate mixing of two or more grain lots to establish the overall quality of the mix as different from any lot alone. Blending also includes the mixing of materials commonly found in grain but not technically grain by the Standards definition of grain (for example, broken grains but not pure FM or dockage). Introduction of pure FM as defined in the Standards was made illegal by the Grain Quality Improvement Act of 1986.

Blending occurs for three reasons: 1) There are economic incentives for grain to be at a specific quality, no better or worse; 2) uniformity of the blended product makes it better suited to handling, storage, or utilization; or 3) some aspect of a particular use process requires a specific quality or range of quality in preference to other possible qualities. The present U.S. marketing system emphasizes soundness and purity properties of general interest so the first two are most applicable. However, as more specific user properties (e.g., protein, oil, starch) enter trade practice, situations will occur when a blended product will be more user valuable.

The Grain Quality Workshop report, Commitment to Quality, also stated that the reasons for blending are to match delivered quality to specified quality and to provide uniform lots (NAEGA, 1986).

Blending for purely economic reasons draws public criticism. However, the phrase "for economic reasons" automatically means that a certain quality level is an acceptable match with the agreed-on sale price. An individual seller will receive maximum revenue from approaching the contract standard as closely as possible, assuming that high-and low-quality stocks are available for blending to meet the contract. On the other hand, sellers as a whole may not receive maximum value or market penetration if pricing practices and institutional constraints force a heavily blended product to be the most commonly traded product. The resolution of the individual welfare versus market welfare issue is one in need of economic study even though there is great difficulty in establishing the potential demand for higher-quality, less-blended grains (Anderson, 1975).

7.2. Mathematical Background

The basic mathematics of blending are relatively simple. The quality of a blend is the weighted average of the lots being blended.

$$X_j = \frac{\sum^{n} (W_i X_{ij})}{\sum_{i=1}^{n} W_i} \qquad (7\text{-}1)$$

where:

X_j = lot quality for the jth quality factor

X_{ij} = quality of sublot i (of n) for the jth factor

W_i = weight of the ith sublot

The application of (7-1) is straightforward when j is 2 or less. However, if several characteristics have economic value, then a profit function must be set up in terms of all relevant factors. The optimum blending proportions of the n sublots is the one that yields maximum profit. Many more considerations - storage space, market expectations, and so on - must be included. Linear programming methods have been used to analyze complex blending problems (Ladd and Martin, 1976).

If there is more than one factor being controlled (j > 1) then, intuitively, one can argue that the blend is most easily optimized if the n sublots are each concentrated in one quality factor but not the others. This will minimize the effect of blending for one factor on all the others. If the X's are small numbers (e.g., low percentages), then concentrating the sublots in individual factors will minimize the volume of secondary streams entering the mix. This explains why cleaning and reblending of broken grains and/or FM is preferred over blending two grain streams of differing percentages. It is also easier to hold a uniform blend when controlling a small flow rate of pure FM or pure damage or clean high moisture grain.

U.S. grain elevators are designed to store large masses of relatively uniform grain of some intermediate quality, with small special storages for lots concentrated in one quality factor (high moisture, high damage, BCFM, etc.). This design is possible because the most heavily traded Grades allow the majority of grain to fall within their broad limits and thus to be stored en masse. As additional user-specific quality factors are introduced, this design and management philosophy may have more difficulty. There will be more factors to consider in profit maximization. The intrinsic factors (for example, nutrient composition) cannot be as readily concentrated or manipulated as the current physical factors. Additional specificity in quality testing will generate a new interest in elevator design. In the short run, handlers may try to eliminate some of the current factors as blending criteria to open up scarce blending space for new factors. This would be possible if the USA had an across-the-board incentive system to improve the soundness and purity factors. From a practical point of view, moisture and foreign material are the easiest factors to eliminate. Single-kernel moisture testing and a greater awareness of the benefits from cleaning could reduce two of the most vexing U.S. quality problems--moisture blends and foreign material--in the natural course of transition to an end-user-oriented marketing system. The next conclusion is that greater emphasis on user quality factors will have an uncertain effect on grain management, depending on what supporting incentives are introduced to relieve the need for segregation on the current soundness factors.

7.3. Blending Practice

Handlers do not solve complex mathematical formulas to adjust blending proportions as they move grain. In corn and soybeans, moisture, BCFM (FM), and damage are the usual factors of concern. FGIS data show that, normally, the particle size (BCFM or FM) factor is limiting (USDA, 1987 a,b). Table 7-1 shows a typical example of four soybean lots being combined to make a U.S. No. 2 grade. The lot analyses are typical of U.S. soybeans (USDA, 1987b; Hurburgh, et al. 1988). Separately the four lots would average $5.91 per bushel; together, they are worth $6.00. The equal-proportions blend is not necessarily the highest-profit blend, but would be quite likely in practice.

Lot	Moisture, %	FM, %	Damage, %	Value,[a] $/bu
1	11.5	1.0	1.0	$6.00
2	14.5	1.2	1.0	5.82
3	12.5	1.0	5.0	5.94
4	11.5	4.0	1.0	5.88
Average value				5.9
Blend of equal proportions	12.5	1.8	2.0	6.00
Contract specification	13.0	2.0	3.0	6.00

[a] Based on typical discount schedules relative to U.S. No. 2. Base price $6.00/bu.

Table 7-1. Blending of four soybean lots to make U.S. No. 2, maximum 13% moisture.

If the FM were removed and reblended as pure FM, then more wet beans (lot 2) and more damaged beans (lot 3) could be blended without exceeding the specifications. Likewise, if lot 3 were more concentrated in damage, it would exert more effect on the damage percentage and less on the other factors.

For an individual handler, the economics of blending are very powerful. The example did not consider the additional revenue potential from the usual interior practice of trading one grade level better than export on all factors. Hill (1985) summed up the issue by questioning whether a low-quality lot suddenly became any more valuable to a buyer when mixed with a high-quality lot. An analysis of this question will be given in section 8. Overall, however, profits from blending are possible only if the average quality of grain normally exceeds contract or grade specifications. The closer the specifications are to the available average quality, the less potential for blending.

Operationally, blending is accomplished with varying degrees of sophistication. At export, barge, and major rail terminals, grain is continuously sampled as it is being added with a mechanical diverter sampler. Samples are analyzed by a "house grader." Changes in the mix are made from the house grader's results. The house grader will test samples even if Official grades are used for price settlement because Official grades are not available quickly enough for on-line management decisions.

Generally, the elevator will target for a quality somewhat better than the Grade standard to protect against the chance that the normal variability in loading, sampling, and analysis will give a result over limits. Woodall (1986) presented the target values an elevator would set to give no chance of being graded over specifications (Table 7-2). If a handler chooses to load quality closer to the Grade limits, then the handler accepts a risk that the grain will be certified as over limits.

The single inspection figures represent the inspection of one lot (truck, barge, vessel sublot) with no appeal. The cu-sum figures represent loading vessels against the cu-sum loading plan utilizing two appeal procedures. These are the most likely scenarios for interior and export inspection, respectively.

Modern elevators have proportioning gates that control the flow of individual lots to the blend. For elevators equipped with one of the cleaning/reblending options (see section 6.2), cleaner throughput and reblending rate will be controlled from the loadout control panel as well. If current blending incentives remain, new quality sensing technologies will be applied to give yet more precise control over blend proportions.

Older country elevators do not have continuous sampling and automated flow control. Quality results are not available until after the grain is loaded.

Grain	Factor	Target values for 100% acceptance Single inspection	 Cu-sum with 2 appeals[b]	Grade Standard
Corn (US No.3)	Moisture[a],%	14.5	14.8	15.0
	BCFM,%	3.6	3.9	4.0
	Damage,%	5.8	6.7	7.0
Soybeans (US No.2)	Moisture[a],%	12.8	12.9	13.0
	FM,%	1.6	1.9	2.0
	Damage,%	2.3	2.8	3.0

[a] Moisture not in Grades; 15.0% and 13.0% assumed specifications.

[b] The cu-sum plan is used to combine inspection results on several sublots into an overall average. Board appeal not included.

Table 7-2. Quality values that have a 100% chance of acceptance as U.S. No. 3 corn and U.S. No. 2 soybeans. After Woodall (1986) and Shipman (1987).

8. EFFECTS OF BLENDING ON QUALITY

8.1. Moisture Content and Moisture Content Uniformity

Moisture blending is most common at interior points, where high-moisture grain is more available. Handlers and growers in the U.S. Corn Belt routinely capitalize on cold weather to store moderate-moisture corn (up to 20%) and soybeans (up to 15%). Furthermore, carry-over stocks from a previous marketing year are usually much drier than market limits, offering an opportunity for blending with fresh wet grain from the field at harvest.

Moisture will never fully equalize in blended lots. If the spread from high to low is less than four percentage points, as recommended by NAEGA (1986), the blended lot will equalize within about 1 percentage point (Nuygen et al. 1984). In some studies, individual kernel moisture spreads of up to 4 percentage points have persisted after several months of storage.

The disaggregation of high- and low-moisture blends is commonly accepted among grain handlers, although there has been no extensive study to validate its existence. Christensen and Kaufmann (1969) alluded to the statistical certainty of some wet pockets within masses of blended corn. Variable moisture causes spoilage in storage and in transit (Christensen and Kaufmann, 1969; DeHoff et al. 1982).

Moisture meters measure average sample moisture. Procedures designed to provide representative samples involve mixing subsamples drawn from individual locations within a lot. The net result is that there is presently no way to detect moisture blends, and no way to control the diversity of moisture being put on a shipment.

The primary reason for moisture blending is obviously economic. The future consequences of large spreads are severe in storage losses. However, there is rationale for establishing a single optimum moisture standard. Relative corn breakage susceptibility increases about 40% for each one percentage-point reduction in moisture content (Dutta, 1987). Relative soybean breakage susceptibility increases 22% per percentage-point reduction in moisture (Hurburgh et al., 1988). These relationships were developed on slow-dried material, to estimate the true moisture effect independent of the drying method effect. Moisture management is a balance between handling breakage and storability. There is simply not enough known about the dynamics of grain storage to establish definitive rules on moisture blending.

8.2. Particle-Size Factors

The blending for particle-size factors has probably stirred the most controversy because these include foreign material and dust. Blending for BCFM in corn and FM in soybeans occurs mainly at interior and export terminals. Corn rarely contains over 2% BCFM at harvest (Iowa Development Commission, 1977); soybeans rarely over 1% FM (Hurburgh et al., 1988). Blending of particle-size factors is essentially a defensive operation to minimize the economic effects of constant handling breakage. There would seem no operations benefitted by having grain at specific BCFM (FM) concentrations as opposed to being clean. Indeed, there may be substantial benefits from not having BCFM or FM in grain.

Uniformity of particle-size distribution makes representative samples easier to obtain. However, a uniformly blended stream will not stay uniform after it has been discharged into a truck, barge, bin, or other container. Hurburgh and Bern (1983) found 1 to 4-percentage-point variations in particle-size factors within truckloads; Hill et al. (1979) documented segregation of up to 10 percentage points of BCFM in vessel holds. No amount of blending will eliminate the nonuniformity experienced by receivers of U.S. shipments. The only cure for particle size nonuniformity is the removal of material that normally segregates. This was discussed in more detail in the previous cleaning sections.

8.3. Damaged Kernels

Blending for damage is a purely economic operation that exists because normal damage levels are less than allowed in the commonly traded Grades. Corn is normally harvested with about 2% damaged kernels; soybeans with less than 0.5%. The Grade limits for No. 3 corn (7% damage) and No. 2 soybeans (3% damage) are wide enough to accommodate blending of any unusual or storage-damaged lots. As the amount of duration of storage increases in response to government program incentives, the amount of damage blending will increase.

Iverson (1986) found that the negative effect of soybean damage on free fatty acid content was a continuous linear scale. In unpublished tests, a major grain company has found that damaged corn kernels contain much greater amounts of mycotoxins and are about 15% less dense than sound kernels. The point is that the first percentage of damage may be as detrimental as the last percentage. The rationale for setting tolerant Grade limits is questionable. Careful storage management is not encouraged. Customers are not receiving the best possible product.

8.4. Intrinsic Factors

The inclusion of intrinsic factors such as protein, oil, starch, and kernel strength will present blending challenges. For these factors, there may well be optimal values or combinations of values.

Soybean processing value depends on both the protein and the oil content (Brumm and Hurburgh, 1987). Blending soybeans of differing protein and oil to obtain the optimum combination will not be a simple task. Table 8-1 shows the regional variability in soybean nutrient content for the 1986 crop. Contracts written with specific standards will require considerable skill and effort to fill. Taiwan now has protein and oil specifications in its soybean contracts (Huffman, 1987).

Region	State	Number of samples	Protein		Oil	
			Percent	Std. dev.	Percent	Std. dev.
Western Corn Belt	Iowa	52	35.27	1.10	18.41	0.59
	Kansas	2	35.08	2.89	19.24	1.45
	Minnesota	41	35.48	1.14	17.99	0.63
	Missouri	29	35.57	1.55	18.86	0.80
	Nebraska	19	35.01	1.37	18.85	0.44
	North Dakota	2	35.26	0.25	17.76	0.23
	Oklahoma	2	34.50	0.22	19.20	0.28
	South Dakota	13	35.43	1.20	18.24	0.73
Averages	Western Corn Belt	160	35.35	1.24	18.43	0.72
Ranges	Western Corn Belt		31.61-37.99		16.74-21.11	
Eastern Corn Belt	Illinois	61	35.49	1.20	18.61	0.67
	Indiana	58	35.78	1.14	18.62	0.61
	Michigan	7	35.47	1.24	18.08	0.46
	Ohio	34	35.54	1.24	18.65	0.68
	Wisconsin	3	34.62	2.63	18.71	0.98
Averages	Eastern Corn Belt	163	35.58	1.22	18.60	0.65
Ranges	Eastern Corn Belt		32.05-38.22		16.97-20.24	
Midsouth	Arkansas	6	36.72	1.37	18.58	0.66
	Kentucky	9	36.31	1.46	18.81	0.73
	Louisiana	8	36.52	1.64	19.41	0.82
	Mississippi	19	37.09	1.47	18.37	0.70
	Tennessee	7	36.[illegible]4	1.39	18.68	0.75
	Texas	1	38.70	--	18.07	--
Averages	Midsouth	50	36.81	1.46	18.68	0.78
Ranges	Midsouth		34.24-39.89		16.78-20.70	
Southeast	Alabama	2	37.67	0.10	18.99	0.07
	Georgia	1	37.28	--	19.29	--
	North Carolina	7	36.92	0.98	18.66	0.45
	South Carolina	8	37.33	1.44	18.44	0.76
Averages	Southeast	18	37.20	1.12	18.63	0.61
Ranges	Southeast		35.56-40.03		16.88-19.47	
East Coast	Delaware	1	35.88	--	18.61	--
	Maryland	6	37.73	0.53	17.94	0.38
	New Jersey	3	35.49	0.04	18.75	0.31
	Virginia	2	38.04	1.11	17.98	0.05
Averages	East Coast	12	37.07	1.21	18.17	0.50
Ranges	East Coast		35.46-38.83		17.42-18.98	
Averages	all samples	403	35.76	1.39	18.54	0.70
Ranges	all samples		31.61-40.03		16.74-21.11	

Protein and oil percentages basis 13.0% moisture.

Table 8-1. American Soybean Association 1986 soybean quality survey data.

9. BLENDING IN THE U.S. GRAIN MARKET--INTERACTIONS

9.1. Grades and Standards

Numeric grades establish a small number of categories for grain quality. They are liked because they provide interchangeability of shipments and minimize special handling requirements. There can be no doubt, however, that numeric grades encourage blending to the lowest possible quality allowed by the contracted Grade. Under present conditions, there is no overt reward for providing quality in excess of minimums. The only benefits for high quality are indirect, as cost savings and other operational gains from handling a more stable product. Competitive pressures may include the value of quality in an overall price level or basis structure, but an individual grower or handler cannot identify quality components and will therefore not seek to improve quality in response (Anderson, 1975).

9.2. Contract Practices

No buyer or seller is forced to use the Standards exactly. Local market practice and contract specifications will exert great influence over the actual amount of blending that can be done.

9.2.1. Domestic

The domestic market rarely buys on numeric Grade Standards. Rather, discounts are assessed factor by factor relative to established market norms. For corn and soybeans, the domestic norms are one grade better than the usual export contract grades. Blending is automatically restricted by the use of tighter limits. Problems are not created because, normally, the particle-size factors are the only ones approaching the limits for either domestic or export markets. Export sales involve more handlings, which mean more breakage and more FM.

Domestic consumers are taking advantage of the higher quality available in the interior to set limits that will protect them from receiving a heavily blended product. For example, high-damage corn is more likely to be directed to export for blending into No. 3 corn than to a domestic processor buying No. 2 corn. Likewise, poorer-quality soybeans are more likely to fit in No. 2 export cargoes than in No. 1 purchases by domestic processors. The combination of domestic market practice and the numeric export standards directs the lower-quality grain to export channels.

Domestic market sellers, especially producers, benefit from "paper blending," the averaging of individual lot qualities for price purposes. This practice is also called load averaging. An example was given in Table 7-1.

Load averaging is not a required practice. From the example, it is obvious that the buyer will pay less by not load averaging. In addition to sharing the benefits of blending with sellers, load averaging reduces the effects of inspection variability, which always cost sellers more than buyers.

9.2.2. Export

There is a trend in export contracts to override the numeric grades with more restrictive specifications. For example, Taiwan specifies maximum 1.5% foreign material in their No. 2 soybean cargoes. Several buyers have reduced moisture specifications. Industry sources estimate that 50% of current U.S. export corn contracts contain special provisions overriding some aspect of the Grades or Official procedures. Prohibiting the use of the cu-sum inspection plan is a common procedural demand that has the effect of forcing the exporter to load slightly better quality than would have been loaded under cu-sum.

Special provisions reduce blending opportunities. The more contract specifications approach the best quality normally available, the fewer possibilities for blending low-quality material. A question to be asked is whether the USA wants buyers to make special orders for higher quality relative to a mediocre quality base or to make special orders for lower quality relative to a high-quality base. Certainly world market competition may prevent the USA from automatically receiving extra compensation to meet special quality specifications, if those same specifications will be met at a lower price by competing suppliers.

9.3. Handling Rates and Warehouse Design

Blending incentives have significantly influenced the design of elevators and farm storages in the Corn Belt. Two corn grades (No. 2 and sometimes No. 3) and two soybean grades (No. 1 and sometimes No. 2) are traded in the domestic market. Therefore, storages do not have to be segmented to accommodate many quality variations. Consider the elevator diagram in Figure 9-1. This is a typical Iowa rail terminal.

The cluster of concrete silos near the tracks is the "workhouse" where grain is stored in preparation for shipment. Longer-term storage is done in the 500,000-bushel tanks and in the "stadium storage." Unit-train shipments are typically 60,000 bushels or more -- similar to barge shipments of 50,000 bushels per barge. Corn and soybean elevators simply are not designed to store and ship to a large variation in quality specifications, except if the specifications are based on particle-size factors. Particle-size factors can be mechanically controlled and thus do not require "special" storage needs. The factor-by-factor discounts used in domestic trade further reduce the incentive to maintain differing qualities.

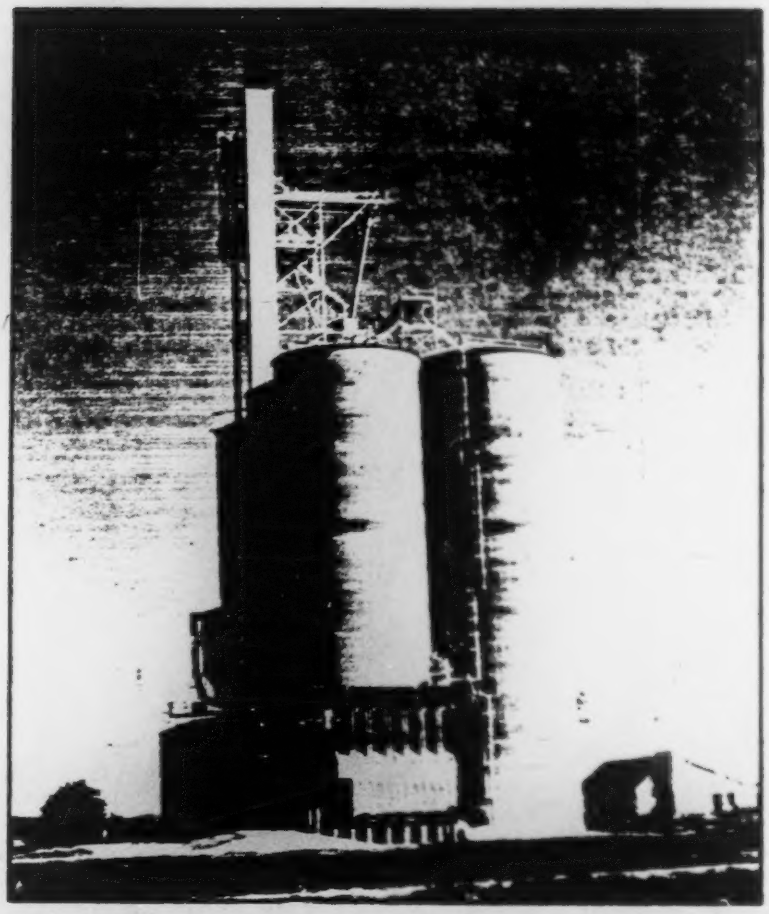

Figure 9-1. Layout of a typical Corn Belt rail-loading elevator.

There will be handler resistance to additional quality factors, particularly those that cannot be changed mechanically, as long as all the old factors still remain economically important. Large "mega-handlers" with as many million bushel storages as most elevators have 50,000-bushel workbins will have a significant advantage if more specifications are used. They will be able to segregate on the volume necessary to make the additional testing and effort economically viable and attractive to buyers. At the other end of the spectrum will be specially designed "identity preservation" elevators catering to limited but quality-conscious markets, such as food-grade soybeans, or snack-food corn. There will be a great need for research and thought relative to elevator design for a quality-conscious market.

9.4. Diversity of Crop Production

There are 47 states contributing to national corn production statistics and, 29 states, to national soybean production statistics. Weather, genetics, and agronomic differences virtually assure quality differences within and across crop years. These differences exist for whatever factors are used to describe quality. A recent example was the high-damage southern soybean crop of 1985 caused by a hurricane and late-season rains. Blending to tolerant Grade Standards evens out these differences, offering long run consistency especially in the export market. A question of great importance is how much protection against acts of nature can the USA afford to retain in its system. Tolerant Grade Standards are a risk-control measure because they reduce the chance that there will be no market for low-quality grain. Tighter Standards on defect factors would raise the average quality but would also increase the probability that some sellers with abnormal quality will face severe discounts. For reasons well documented by Anderson (1975), no single buyer or seller can afford to set these tighter Standards.

The inclusion of intrinsic factors will magnify the regionality problem. Table 9-1 presented data on regional soybean protein and oil content. Blending will have to occur if fixed specifications are set for export soybeans. Even if protein and oil are priced on a continuous ~~scale~~, with no mandatory targets, growers in some areas will face discounts relative to growers in others.

9.5. Administration of Grain Storage Programs

Grain stored under warehouse receipt, whether issued to farmers or to USDA, is subject to a quality guarantee stated on the receipt. Regardless of the quality delivered, the warehouseman is responsible to maintain storage of grain to meet the specifications on the receipt. It is usual practice to use a U.S. Grade number with the factor limits set in the Grades, rather than the actual delivered lot quality, as the guarantee on a warehouse receipt. A government warehouse inspection (either State or Federal) verifies that an elevator has sufficient quantity and quality on hand to cover warehouse receipts. However, no specific physical lot of grain is assigned to specific receipt(s), so the warehouseman is free to blend and rotate stocks with the only criterion that the net deliverable grain be of minimum acceptable quality or better. Blending offers flexibility to the warehouseman and greater assurance to the receipt holder that a warehouse will not get into an insolvent situation, which could be a loss for the holder as well as the warehouse. Because the USDA is the largest holder of warehouse receipts at this time, USDA is also the largest beneficiary of benefits from blending.

10. Blending--Quality Control or Quality Reduction

The central issue in blending is whether it is a positive or negative economic factor. Alternatively, do Standards constructed with intent to encourage blending act in the long-term benefit or detriment of the USA?

10.1 Defect Factors vs. Intrinsic Factors.

The list of important quality factors can be conceptually divided into two categories those that are defects (or will potentially cause defects) and those that are more specifically tied to individual end uses. The line is not always clear--where to classify broken corn, for example. Defect factors are of negative value to all users, whereas user-sensitive factors will be evaluated differently, even oppositely, by different users. Primary examples of defects are foreign material and damage. Examples of user-sensitive factors are compositional analysis and breakage susceptibility. Arguments to "tighten Standards" carry much more weight when applied to defect factors than to user-sensitive factors.

Accepting that defect factors have negative value for all users would suggest that blending for these factors will not improve the value of grain and that the aggregate value of blended lots will not be higher than the separate values of individual components (Hill, 1985). If a major segment of the market for U.S. grain has other alternatives for supply, then trading practices that allow an increase in defects may well be to the aggregate disadvantage of U.S. sellers. Market limits in excess of technologically feasible defect levels do not provide specific handlers as strong an incentive for constant vigilance on quality as would Standards and practices set close to the best realistically achievable levels. The U.S. market as a whole is worse off if defect amounts are greater than necessary.

Blending can be neutral or even beneficial for user-sensitive factors. If the value of factors can be determined on a linear continuous scale (e.g., protein and oil in soybeans) then deliberate blending will neither hurt nor help. However, if the use process is nonproportionally sensitive to quality above or below some known value (e.g., free fatty acids), then blending will be beneficial. Processes may also have to be adjusted to make most use of differing qualities (e.g., steeping time in wet milling), which means that test results tightly clustered around some mean value(s) will be preferred over wide random distributions.

Blending runs into difficulty in user-sensitive properties when, for various reasons, the market uses trading limits not in synchronization with effects on users. For example, moisture is a mathematical adjustment to the amount of organic material available. Users close to supplies probably will be less concerned about the deteriorative potential of mixed-moisture grain. However, mold and insect response is nonlinear in moisture; spoilage risk increases rapidly if grain is at moistures in equilibrium with 65% air relative humidity or higher (Christensen and Kaufmann, 1969). The prevalent 15% and 15.5% corn moisture limits have humidity equilibria in excess of 65% at temperatures over 60°F. En-masse humidities are even higher if the lot is composed of a mixed moisture blend because the hysterisis property of equilibrium moisture content prevents the wet and dry kernels from equalizing.

10.2. The Value of Uniformity

Uniformity is generally very desirable in a grain lot. Blending to achieve uniformity within a shipment is almost without exception an advantage to the buyer. The correctness of the present Standards for defect factors is a totally separate question from the correctness of blending. Given that the Standards set loading target values for shipments, the targets are much better reached by distributing the lower quality (FM, damage, etc.) uniformly rather than in erratic patterns. Cargo uniformity will become even more important if user-related properties become common criteria.

Therefore, thought should be directed at those elements of inspection procedures that do not encourage blending for uniformity. Changes in Standards may deemphasize blending for some factors, but the emergence of new factors will present new requirements for uniformity.

Sampling is probably the most important inspection procedure bearing on uniformity. The NAEGA (1986) report cited probe-sampling of barges as a major source of problems. Barges are probed up to 12 times. The individual probings are mixed to form the inspection sample. Mixing of probe samples compensates in part for nonuniformity in the loading of the barge.

The point to be made is that deliberate blending will always occur and is not, in itself, detrimental provided that inspection procedures, test equipment, and Standards assure that cargo uniformity is the end result. Establishment of appropriate Standards is a separate issue that should not be confounded with an assessment of blending as a handling operation.

10.3. Changes in Blending Practices Needed for Proposed Changes in Standards or Market Practices

Any proposal to tighten or remove Grade factor limits has the practical consequence of reducing blending opportunities. Examples are dry-basis pricing, lower damage limits, and zero foreign material limits. In each of these cases, pricing of quality factors is placed on a continuous scale rather than on a step function. Reduced blending also means fewer separate storages for blending materials. Ironically, most proposed changes to the defect factor Standards will simplify handling decisions by deemphasizing the in-house movement of off-grade grain.

The establishment of two corn particle-size factors would have an impact on blending operations. If broken corn (BC) remains a Grade-limited factor, then blending to BC limits will be complicated by the presence of the smaller FM particles. It is the author's opinion that elevators will have to be equipped with low-capacity secondary cleaners to remove FM from BC. As an example, if a primary cleaner was removing 3% BCFM from a 40,000-bushel-per-hour stream, the secondary cleaner would have to handle only 1200 bushels per hour. A rotary cleaner of this capacity currently costs about $2,000, not including installation in a handling system. The simultaneous control of two particle sizes without mechanically removing or concentrating either one will not be operationally feasible.

Intrinsic value factors will offer by far the greatest challenge to handlers. The diversity of the U.S. crop will assure that blending will be necessary. Because various users will regard intrinsic quality factors differently, the choice of which lots to include in a shipment will be an economic optimization problem much more complex than the blending of physical properties to meet one or two commonly traded Grades. However, any statements about user-preferences are grain-specific. Nearly all soybeans are crushed into meal and oil; this industry will have uniform preferences for protein and oil percentages. On the other hand corn is fed, dry milled, wet milled and alkaline cooked. User preferences will be varied.

Expectations of future quality availability and future market demand will be more important and subject to greater error. Thus, handlers will face greater risks. At first, they will probably opt to "oversegregate," isolating more individual qualities than necessary, to avoid being caught out of position. Technologically, this will place more burden on the testing and inspection system to produce accurate results quickly enough to be used in grain management as well as pricing. There will be a perceived need for more separate storage spaces, which in turn, should make the transition to lower defect standards more palatable. Storing all clean grain is one way of eliminating one segregation criterion in preference to another.

Kernel-moisture analysis will also have a major impact on grain handling practices. If adopted as a pricing criterion, kernel-moisture testing will eliminate the practice of storing wet grain for future blending. This frees up blending space for other factors but, more importantly, demands greater control over grain drying. If overdrying cannot be compensated by blending, then it will have to be reduced by modifications to dryers, as suggested by Bakker-Arkema (1988). There may also be a tendency to reduce the market moisture basis, particularly by handlers who feel that they cannot exercise any better control over dry grain moistures. Dryer moisture uniformity will become a crucial performance parameter. The large moisture variation that some dryers have across their drying columns could be very detrimental given a market limit on kernel-moisture variation. In some cases, significant new investments in equipment will be needed. Many rapid-turnover elevators (barge-loading, rail-loading) use blending to dispose of wet grain, rather than operating a dryer. Their options will be to dry or to discourage the delivery of wet grain.

11. NEW TECHNOLOGIES AND RESEARCH NEEDS RELATED TO BLENDING

11.1. On-line Automated Control Systems

Control sophistication is advancing rapidly in the grain industry. The profit opportunities of blending make blending control one of the most active equipment development areas in the grain industry. This development will proceed with or without Standards changes, but the introduction of intrinsic factors will accentuate the need for rapid sensing equipment as well as grain flow control equipment.

From a loadout point of view, blending control consists of adjusting several flow streams to hold the mix as close to specifications as possible. Section 9 described how this is presently done. It is a manual operation with an operator translating quality information into action. Currently available new equipment, which electronically senses flow in spouts, moisture content of flowing streams, and grain depths in bins will be of value in eliminating operator involvement. Areas of development potential are 1) on-line computer vision, a concept already accepted in fruit and vegetable processing; 2) microcomputer control of proportioning gates; and 3) various spectrometric methods of rapid sensing of grain properties. Development of blending control technologies will proceed without external support or research because there is economic advantage to be gained by approaching ever closer to contract specifications. Changes in Standards and inclusion of additional factors can influence the directions of development. Given current Standards, U.S. handlers will readily accept technologies that will enhance their ability to blend for the current set of Grade factors.

At receiving, the need is to assess quality rapidly enough to make handling and storage decisions. The more factors are important, the more sensing and communications technology will be required. The most important area of research will be the latter; in communicating grain-quality test data either to persons or automatic equipment that will direct each grain lot to its appropriate storage. This is not a trivial matter; many country elevators receive a load every one or two minutes during harvest. Rapid analysis of quality, then maintaining proper assignment of the grain in the dump queue, is a major concern retarding interest in specialized factors. Technologically, most elements of test and communication systems are available, but significant application research will be needed to fit them together in the grain elevator scenario. Unlike loadout blending control, this is an area that probably will not generate its own momentum. The incentives for such developments are not currently in place; it is likely to be easier to resist the introduction of the incentives than to pay for the technology to capture them. Therefore, public institutions may have to take the lead. An investment of $1-2 million annually (5-10 scientists per year) for 5-10 years would be adequate to establish a base on which industry would eventually build.

11.2. Elevator Design and Management

As discussed, U.S. corn and soybean elevators are designed for storage of one or two quality Grades, with loadout blending of off-grade streams. Some proposed Standards changes would reduce the need for differentiated storages, others would increase it. There is little organized research into overall grain elevator layout design. There has been development of computer models to lay out on-farm handling systems. This is not to say that the components of elevators are incompetently designed. Designers serving the industry respond to existing demand. Several topics not currently supported by market incentives need development:

- System configurations to store clean grain
- System configurations to isolate various intrinsic quality factors.
- Management strategies to capture maximum benefits from expanded quality testing.
- A system approach to determining technological needs in the handling industry.
- The operational impact of more descriptive testing on systems designed to meet present Grades.

The presence or absence of blending probably is the single most important criterion determining design and technological change in the U.S. grain industry.

The nucleus exists at at least three midwestern universities to address these issues, issues that are basically engineering-oriented. Traditionally, engineering programs have not found agricultural problems of paramount importance. However, the several national agencies involved in engineering programming have a significant opportunity to influence activity toward what will be a vital area for the USA--the competitiveness of its agricultural infrastructure.

11.3. Subgrades

A recent study sponsored by the State of Iowa suggested subgrades as a method of balancing end-user specificity with interchangeability (Evans and Livingston, 1987). A subgrade would be an additional grade designation appended to the standard grade statement--e.g. U.S. No. 2 corn, wet milling. There would be a group of factors associated with each subgrade, for instance starch content, endosperm hardness, and so on. Grain receiving a subgrade designation would have met limits for the subgrade factors. Subgrade factor limits would be set to assure that grain receiving a subgrade designation would be substantially better than average to the subgrade user. Subgrades would increase the number of tradeable commodities somewhat, but would retain the liquidity of graded grain. Subgraded grain would also meet the limits of the numeric grade to which the subgrade was appended.

Creating the subgrade packages, and estimating the demand for subgrade grain is not a simple task. The NC-151 regional research group has formed a task force to begin this work. subgrades are an interesting concept. In addition to the technical discussions of formulating subgrade packages, public resources would be well spend supporting a feasibility study of the subgrade concept. This does not have to be done at many institutions; approximately $250,000 well-placed would be sufficient.

12. CLEANING AND BLENDING--GENERAL SUMMARY

The operations of cleaning and blending will be crucial to the success of any program to improve U.S. grain quality. In current practice, cleaning is used to hold corn BCFM or soybean FM levels within Standards limits. Blending is used to control various quality factors as closely as possible to specifications. Ideally, cleaning can be a quality-control operation by eliminating the need to segregate grain by foreign material content, generating significant revenues over costs to storage-based operations and reducing nonuniformity problems in cargoes. Blending is necessary because of the diversity of quality in U.S. grain. Blending requirements will become more sophisticated and complex if intrinsic, user-related properties are substituted for or added to the current defect properties in the Grades.

Cleaning can be accomplished by density separation (aspiration) or size separation (particle screening-scalping). Screening is more common because the Grades use size as the criterion for defining foreign material. Most corn and soybean elevators and some farmers have cleaners, but, in general, cleaning capacity in the USA is not adequate for universal cleaning. Retrofitting U.S. elevators with currently available screening equipment will be costly (several hundred thousand dollars per elevator) and structurally difficult. New, inherently balanced cleaner designs are a very promising technology. Additional cleaning necessitated by more stringent Standards probably will be done in commercial channels, several handlings removed from the grower because initial foreign material levels are less than 1.0% in either corn or soybeans. Additional foreign material is generated with each transfer operation. For corn, a conversion of 6-10% of whole kernel weight to broken corn can be expected, based on 12-20 elevations at 0.5% conversion per elevation.

The size distribution and properties of corn fines have been extensively studied to the extent that further data tabulation will likely yield no additional information. There is no single particle size that clearly differentiates corn foreign material and broken corn. Sufficient information is available to make an economic evaluation of the potential alternatives for the division of corn BC and FM. Case study analyses have shown that the removal of either BC or FM can generate net profits even with present Standards and market practices offering no premium for the cleaned grain.

Aspiration and rotary screen cleaners have the potential to solve many of the operational problems associated with screen cleaners. Any new cleaner design will have to achieve 30,000-40,000 bu/hr to penetrate the commercial terminal market. Smaller cleaners can be used on farms or at country elevators. There is great need for establishment of performance specifications and tests for cleaners. Professional societies such as the American Society of Agricultural Engineers should undertake this task. Research needs include properties of cleanings and public demonstration of the benefits for cleaning, tasks for which public institutions seem best suited. A public investment of $1-2 million per year for five years probably would meet the need.

Blending control is an area of rapid technological development in the grain industry. Nearly all new quality-measurement technologies are first put to use monitoring quality of blending grains. Major recent developments include automatic control gates and their remote operation, flow sensors, and bin level sensors. This development will continue without public funding because there is strong incentive for handlers to blend as close to specifications as possible. If the Standards remain unchanged, then technologies will concentrate on the current Grade factors, with customers receiving U.S. grain ever closer to maximum limits.

U.S. elevators are specifically designed to operate in the blending environment of the current Standards. They store bulks of one or two quality grades, with lesser storage capacity for off-grade materials to be blended on loadout. Changes to the Grades that would place factors on a continuous rather than a stepwise pricing scale will probably simplify operations. Intrinsic factors of potentially differing value among buyers will be difficult to accommodate and will make management decisions more complex. Very large handling operations with many bulk storages will be in the best position to capture initial benefits of more intensive quality specifications.

Blending is necessary to achieve uniformity. It also has created problems in instances where purely economic incentives with no basis in physical benefits caused it to occur. Wide spreads in moisture content virtually assure deterioration in transit, but presently, there is not technology to detect such spreads. However, blending per se is not at fault; blending will provide benefits as long as the incentives of Standards and market practice are focused on uniformity and the creation of optimal value product, rather than on the disposal of undesirable material with the least hardship to handlers. Current practices to a certain extent protect warehousemen and the USDA from the consequences of the extended storage necessary to sustain U.S. farm policy. Nonetheless, blending will be extremely necessary in the future to optimize the diverse intrinsic quality of U.S. grain to individual user needs.

Should blending opportunities for current factors be limited and additional factors be introduced, substantial new plant and equipment investment will be needed. Handlers will need to reevaluate management strategies and storage designs. Control of moisture blending will necessitate dryer additions and modifications, the costs of which are discussed in another paper for this study. Industry likely will continue to advance loadout blending technology. Public stimulus will be needed to develop the rapid sensing and communications equipment needed to receive grain. Many of the receiving and management logistics for intensive quality assessment must be developed in advance of Standards changes, the better to convince handlers and growers that such a system is feasible. A 10-year, $1-2 million annual public commitment will be adequate to provide groundwork for industry to build upon.

Cleaning and blending are enigmatic operations in the continuum of grain-quality debates. They can be used defensively to create many of the situations our customers have come to question, or they can be the core of a consumer-oriented quality allocation program. Technologically, the USA is capable of applying them in either manner. Which we choose will have great bearing on our future market image.

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Grain Drying Technology

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CHAPTER 1

INTRODUCTION

Cereal grains and oilseeds are usually combine-harvested in the United States at moisture contents which are too high for long-term and even short-term storage, or for transportation within the marketing system. Thus, these commodities must be dried or dehydrated -- the process in which the kernel or bean moisture content is decreased to a safe storage moisture content. For corn, the major crop dried in the United States, the harvest moisture content is 20-30 percent (wet basis)[1], the storage moisture content 14-15 percent. For wheat and soybeans, the harvest moisture content is substantially lower (i.e. 16-19%), the final moisture only marginally lower (12-14%) than for corn. In certain regions of the country (e.g. Kansas), wheat dries totally in the field; in some years this is also true for soybeans. Thus, this report is mainly concerned with corn.

Considerable moisture is removed from grains in the drying process (see Table 1.1). For the drying of corn from 25 to 15.5% moisture, 122 kg of water is removed per metric ton of grain or 220 kg per acre (assuming a yield of 100 bu per acre). The energy required for this drying process is 0.4-0.7 million kJ per ton of wet corn. The average energy cost at 1987 natural gas prices is $2.67 per ton.

The drying of grains in the United States takes place on the farm or off the farm at the elevator. Air is the drying medium. On-farm drying systems are lower in throughput (usually expressed in terms of bushels of wet grain dried five moisture content percentage points per

---

[1] All moisture contents in this report are expressed on a percentage wet basis where MC (w.b.) is defined as 100 times the ratio of the weight of the water in a grain sample to the total weight of the sample.

Table 1.1. Moisture to be removed, energy requirement and cost for drying one metric ton of wet corn to 15.5% (wet basis).

MC Initial (% w.b.)	Moisture Removed (kg)	Energy Required* (kJ)	Energy Cost** ($)
30	171	876,295	3.93
25	122	574,125	2.67
20	53	271,955	1.22

*Assuming an energy use of 5117 kJ/kg of water

**Cost of natural gas $4.48/10^{6}kJ

Source: Bakker-Arkema(1986)

hour) than off-farm units, and frequently employ lower drying-air temperatures. Liquid propane, natural gas, and occasionally fuel-oil, are used as the energy sources. The energy efficiency of a drying system is expressed in terms of kJ per kg of moisture removed from the grain.

The design of drying systems is grain-type dependent. The requirements for the drying-air temperature, the airflow rate, and the dryer residence time (i.e. the time grain remains in a dryer) are different for corn, wheat and soybeans. Thus, the drying of wheat in a corn dryer without modifying the operating conditions, leads to a significant decrease in grain quality of the wheat.

It is generally agreed (Hamdy et al.,1977) that the bulk of the grain-quality deterioration occurring in the harvesting/drying/storage/transportation chain happens during the drying process. Too frequently, excessively high drying-air temperatures and airflows are employed in order to increase the drying rate. This leads directly to the excessive stress-cracking of corn and soybeans (Ghaly and Sutherland,1983), and to the degradation in the milling quality of wheat (Ghaly and Taylor,1982).

This paper reviews the state-of-the-art of grain drying technology, in particular of the effect of dryer design and dryer operation on grain quality. The grain quality attributes considered in this report include stress-cracks and breakage susceptibility for corn and soybeans, and milling quality for wheat; the dry-milling quality of corn has been considered by Paulsen and Hill(1985). On-farm and off-farm U.S. and overseas drying systems are analyzed. The interaction of the drying process with the preceding process (i.e. harvesting) and the subsequent processes (i.e. handling/storage/transporation) is considered. Finally, a number of promising new and emerging drying technologies are evaluated, and their research needs, implementation costs, and impact on the grain quality of the United States grain crop, are analyzed.

CHAPTER 2

PRESENT GRAIN-DRYING TECHNOLOGY

Cereal grains and oilseeds are dried in the United States mainly on the farm. Typical is the State of Indiana where in 1984 less than 5% of the corn was dried off the farm and over 80% on the farm (ICLRC,1984). In some countries (e.g. France) the situation is reversed, as most of the drying takes place at the elevator level. In the Third World, the bulk of the grain is still dried by spreading the wet grain on the ground in thin-layers in the open air in the so-called sundrying process.

In this section the main on-farm and off-farm drying systems encountered in the United States and overseas are described.

On-Farm Systems

The throughput of on-farm dryers is in general considered to be less than 12.5 tons per hour. They fall into three broad categories: (1) bin dryers, (2) non-bin dryers, and (3) combination drying systems. Table 2.1 lists the most common on-farm dryers used in the State of Indiana in the early eighties; the distribution is typical for the Midwestern United States.

Bin Dryers

Bin dryers include: (1) in-bin natural-air dryers, (2) in-bin low-temperature (or supplemental heat) dryers, (3) solar dryers, (4) in-storage layer dryers, (5) in-bin counterflow dryers, and (6) batch-in-bin dryers. Bin dryers employ a bin for holding the wet grain as it is dried. The drying-air temperature of systems (1) through (4) is relatively low, between ambient and 40°C; systems (5) and (6) employ drying temperatures as high as 70°C. The airflow ranges from 0.5 to 15 m^3/min t.

Table 2.1. Percentage of different on-farm dryer types used in the State of Indiana in different years.

Dryer Type	1980	1981	1982	1983
Portable Batch Dryer	26.5	28.4	27.3	20.7
Batch-in-Bin Dryer	15.8	17.0	17.1	15.0
Continuous-Flow Dryer	40.1	30.6	33.3	35.8
In-Storage Layer Dryer	14.4	17.2	18.6	21.5
Other	3.2	6.8	3.7	7.0

Source: ICLRC(1984)

The rate of change in moisture content and temperature of the kernels is relatively low, a critical factor in maintaining grain of high quality.

In-bin natural-air, low-temperature and solar drying are similar; wet grain is placed in a bin to a depth of 2.5 - 5.0m, and dried slowly using a fan external to the bin as the source of airflow. Each system is able to produce high quality grain. The distinction between the three systems is that no heat (except fan energy) is added in natural-air drying, while for low-temperature and solar drying the air temperature is increased a few degrees (with an electric heater or solar collector) to decrease the relative humidity of the drying air to below 55%. The three drying systems have long been used for small grains harvested during the summer months at moisture contents below 18%. They have been adapted since the oil-crises of the 70's for the drying of higher moisture content grains, including corn. The minimum airflow rate is critical for the success of the three systems, and depends on the initial moisture content of the grain, the harvest date and on the environmental conditions. Table 2.2 lists the minimum airflow rate for natural-air, low-temperature, and solar in-bin drying of corn at different locations in the Midwest. Considerable expertise is required on the part of the farmer to properly operate one of the three systems because of the importance of selecting the correct airflow rate. Low flowrates lead to molding of the grain before the safe storage moisture content is reached. An in-bin natural-air grain drying system is illustrated in Fig. 2.1; a solar system in Fig. 2.2.

In-storage layer drying differs slightly from natural-air drying. Rather than filling a bin at once with wet grain, a bin is filled in layers with each subsequent layer being placed in the bin after the pre-

Table 2.2. Minimum airflow requirements ($m^3 \, min^{-1} \, t^{-1}$) for different locations in the north central region states, assuming an initial moisture content of 24% (w.b.) and a harvest date of October 15.

	Natural-Air	Solar	Low-Temperature
Location	Next to worst year	Next to worst year	Next to worst year
Chicago, IL	3.01	2.41	2.49
Indianapolis, IN	4.57	2.37	2.09
Des Moines, IA	2.43	2.51	2.19
Dodge City, KS	2.48	2.36	2.36
Lansing, MI	3.07	2.56	2.61
St. Cloud, MN	2.13	1.96	1.94
Columbia, MO	2.77	3.10	2.44
Lincoln, NE	2.31	2.23	2.00
Bismarck, ND	0.64	0.60	0.60
Mansfield, OH	2.84	2.12	2.06
Huron, SD	1.56	1.35	1.26
Madison, WI	2.50	2.09	1.97

Source: Pierce and Thompson(1979)

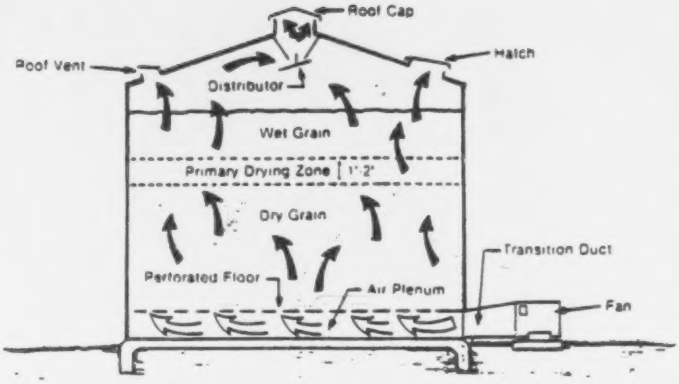

Roof Cap
Roof Vent
Hatch
Distributor
Wet Grain
Primary Drying Zone
1'-2'
Dry Grain
Transition Duct
Perforated Floor
Air Plenum
Fan

Fig. 2.1. An in-bin natural-air grain-drying system.

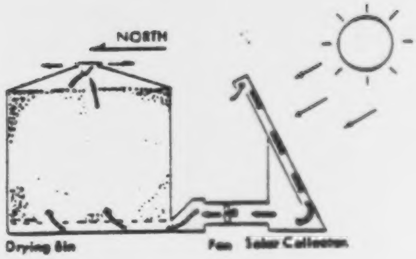

NORTH
Drying Bin
Fan
Solar Collector

Fig. 2.2. In-bin solar grain dryer.

ceding one has (almost) reached the final storage moisture content. In-storage layer drying has similar characteristics as natural-air drying; it has a low capacity, requires considerable operator expertise, is energy efficient, and can produce excellent grain quality.

In-bin counterflow drying is a relatively new system. It consists usually of two bins; one is a heated-air (55-70°C) in-bin counterflow dryer, the other a natural-air in-bin grain dryer and cooler. Wet grain is loaded in the first bin and dried until the bottom 10cm layer has reached a moisture content of 16-18%. The partially dried hot grain is removed by a tapered sweep auger, and transported to the second bin for slow final-drying and cooling. The automatic nature of the process, along with the ability to produce high quality grain at fairly high capacity, have contributed to the commercial success of the in-bin counterflow drying system. Fig. 2.3 shows the in-bin counterflow dryer.

Batch-in-bin dryers differ from in-bin counterflow dryers because they lack the tapered sweep auger and the second drying/cooling bin. The airflow rate (10-15m^3/min t) and drying air temperature (45-65°C) are similar in the two systems. The energy efficiency as well as the grain quality characteristics of the batch-in-bin systems are inferior to those of the in-bin counterflow dryers (Bakker-Arkema,1984).

Non-Bin Dryers

Non-bin on-farm dryers include: (1) portable batch dryers, and (2) continuous-flow dryers. The author estimates that over 50% of the U.S. grain crop is dried in these two dryer types. The units often utilize drying-air temperatures in excess of 100°C and airflow rates over 100m^3/min t. The rate of change in moisture content and temperature of the kernels is high. Thus, the drying rate of the grain kernels is high,

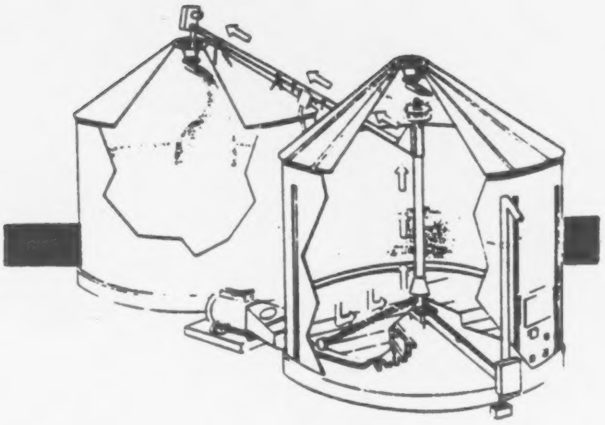


Fig. 2.3. In-bin counterflow grain dryer.

and the resulting breakage susceptibility increase often considerable.

A portable batch dryer consists of a plenum surrounded by a 30-40cm grain column. The high-temperature drying-air traverses the grain layer quickly, in the process overheating and overdrying part of the column, and thereby nearly exponentially increasing the breakage susceptibility of the overdried grain. The batch is removed from the dryer as soon as the desired final average moisture content and temperature of the grain have been reached [note: cooling of the grain takes place in the dryer]. A portable batch dryer is comparable with an in-bin batch dryer except that the grain is dried at a higher airflow rate and temperature in the portable batch unit due to the reduced depth of the grain layer. Fig. 2.4 shows a portable batch dryer.

Continuous-flow dryers used on the farm in the United States are predominantly of the crossflow type. In the crossflow model, the drying air flows perpendicular to the flow of the grain through the dryer. The plenum/grain column configuration is similar to that of the portable batch dryer design. Cooling of the dried grain in the continuous-flow dryers takes place in the bottom one third of the drying column (see Fig. 2.5). The airflow rate and the drying-air temperature in the portable batch and the continuous-flow dryers are the same; the models only differ with respect to the grain velocity.

Continuous-flow crossflow dryers dry grain non-uniformly; a large gradient exists across the grain column at the time the drying process is discontinued. [The same condition exists in batch-in-bin and portable batch dryers.] During the cooling cycle, the degree of non-uniformity decreases, but a definite moisture differential among the kernels still remains at the time the grain exits from dryer. Gustaf-

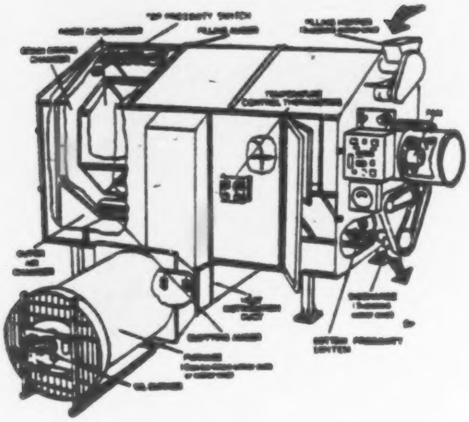


Fig. 2.4. Portable batch grain dryer.

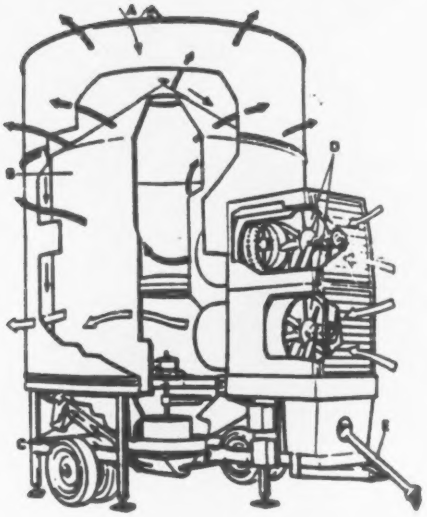


Fig. 2.5. Continuous-flow crossflow grain dryer.

son et al.(1981) quantified the moisture gradient in the grain-column of a crossflow dryer (see Table 2.3); in drying 25% corn at 110°C to an average moisture of 16%, the moisture content of the corn exiting the drying section at the air-inlet side of the grain-columns had reached 8%, while at the air-outlet side the grain was still at 22%, a moisture gradient of 14%. The data in Table 2.4 shows that part of the grain in a crossflow dryer approaches the drying-air temperature; this results in overdrying and a sharp increase in the breakage sus-

Table 2.3. Moisture content gradient (%) in the grain column of a crossflow dryer after drying corn from 25.5% to 16.0% with and without cooling.

Air Temp (°C)	MC Gradient, Non-Cool (%)	MC Gradient, Cooling (%)
82	9.7	8.6
110	14.2	12.2
138	19.4	16.6

Source: Gustafson et al.(1981)

Table 2.4. Grain temperature, moisture content and breakage susceptibility at different locations in the grain column of a crossflow dryer after drying corn without cooling from 25.5% to 19% at 110°C.

Distance from Air Inlet (cm)	Grain Temp (°C)	Moisture Content (%)	Breakage Susceptibility (%)
1.25	102	10	48
7.50	78	20	11
13.75	51	24	10

Source: Gustafson et al.(1981)

ceptibility of this corn. The effect of overdrying on the breakage susceptibility of corn is quantified in Table 2.5; drying to 11% leads to twice as much breakage than drying to 15% moisture content.

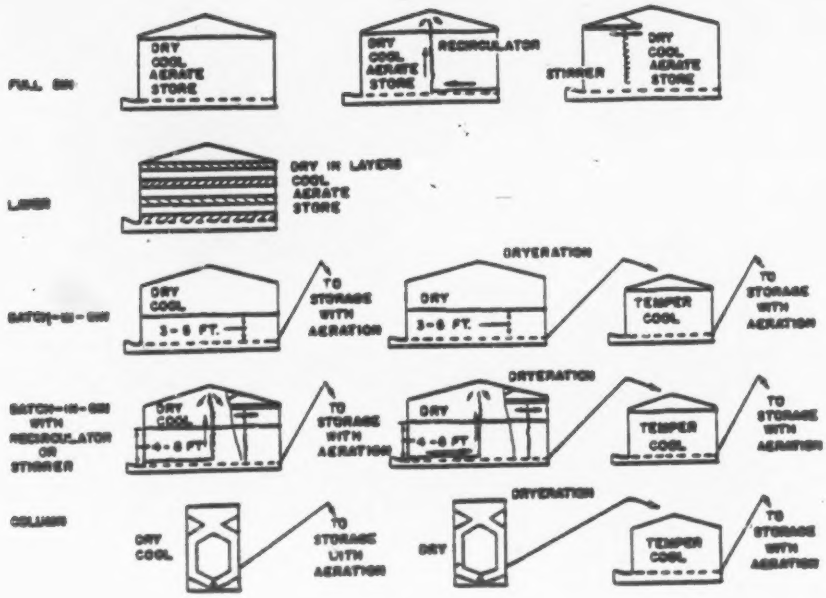
It is obvious from the data in Tables 2.3, 2.4 and 2.5 that crossflow dryers dry grain unevenly, resulting in partial overheating and overdrying of the grain, and in an increase in the breakage susceptibility of part of the grain. Thus, the high breakage susceptibility of the U.S. corn crop is due to a large extent to the fact that over 50% of the crop is dried in continuous-flow, portable-batch and batch-in-bin dryers, each basically a crossflow dryer-type.

Combination Drying

Combination grain drying is defined as a system in which high-temperature, high-rate batch or continuous-flow drying is followed by low-temperature, low-rate in-bin drying and cooling. Combination drying attempts to maximize the advantages, and minimize the disadvantages, of the two systems.

In practice, combination drying is mainly used for corn. The crop is harvested in the 22-35% range, dried in a high-temperature dryer to an intermediate moisture content (18-24%), moved hot to an in-bin dryer, and slowly final-dried and cooled. The in-bin dryer is usually a natural-air dryer. Dryeration is the best known type of combination drying (see Fig. 2.6).

The two main advantages of combination drying compared to high-temperature batch and continuous-flow drying are the increased energy-efficiency and grain-quality of the system. This is illustrated in Table 2.6 in which portable batch drying is compared to three combination drying systems; note the improvement in the energy use and in


FULL BIN
DRY
COOL
AERATE
STORE
DRY
COOL
AERATE
STORE
RECIRCULATOR
STIRRER
DRY
COOL
AERATE
STORE
LAYER
DRY IN LAYERS
COOL
AERATE
STORE
DRYERATION
BATCH-IN-BIN
DRY
COOL
3-6 FT.
TO
STORAGE
WITH
AERATION
DRY
3-6 FT.
TEMPER
COOL
TO
STORAGE
WITH
AERATION
DRYERATION
BATCH-IN-BIN
WITH
RECIRCULATOR
OR
STIRRER
DRY
COOL
4-6 FT
TO
STORAGE
WITH
AERATION
DRY
4-6 FT
TEMPER
COOL
TO
STORAGE
WITH
AERATION
DRYERATION
COLUMN
DRY
COOL
TO
STORAGE
LITH
AERATION
DRY
TEMPER
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STORAGE
WITH
AERATION

Fig. 2.6. A number of dryeration grain-drying systems.

Table 2.5. The effect of the final moisture content on the breakage susceptibility of 25% corn dried at 110°C.

Final Moisture Content (%)	Breakage Susceptibility (%)
18	11
15	18
13	27
11	39

Source: Gustafson et al.(1981)

Table 2.6. Energy use and grain quality of four alternative on-farm drying systems in drying corn from 26-15%.

Drying System	Energy Use (kJ/kg)	Stress-Cracked Kernels (%)	Breakage Susceptibility (%)	Viability (%)
Portable Batch	6584	87.3	46.3	22.0
Batch/Natural-Air	3173	2.8	11.9	66.0
Batch/Low-Temperature	4028	3.4	13.1	60.0
In-Bin Counterflow	4699	64.0	29.0	--

Source: Silva(1980)

three grain qualiity parameters for the three combination drying systems compared to portable batch drying.

Off-Farm Systems

Grain dryers at United States elevators or terminals are continuous-flow models. Three types are in use: (1) crossflow, (2) mixed-flow, and (3) concurrent-flow. The author estimates that over 85% of the off-farm dryers in the United States are of the crossflow type. In those overseas countries where large-scale dryers are employed (i.e. France, Brazil, Thailand), mixed-flow models are predominant (Lasseran,1987).

Crossflow Dryers

Crossflow dryers have been defined in the on-farm section of this chapter. The distinguishing feature is the perpendicular direction of the grain and air flows; this results in the non-uniform drying treatment of the grain. Overheating and overdrying of the grain at the air-inlet side of the grain column, and underheating and underdrying of the grain at the air-outlet side, is inherent in the crossflow design (see Fig. 2.7). Recent design innovations of the basic off-farm crossflow dryer have resulted in improvements in the grain-quality and the energy-efficiency characteristics of this dryer type.

In a conventional crossflow dryer, the discharged air is only partly saturated. Recycling of part of the drying air and all of the cooling air (see Fig. 2.8) greatly decreases the energy requirement (Meiering and Hoefkes,1977). Along with air recycling, reversal of the airflow has been incorporated in some crossflow dryers in order to offset the major disadvantage of this dryer type, the large moisture differential in the grain column (Pierce and Thompson,1981). Placing a grain-invert-

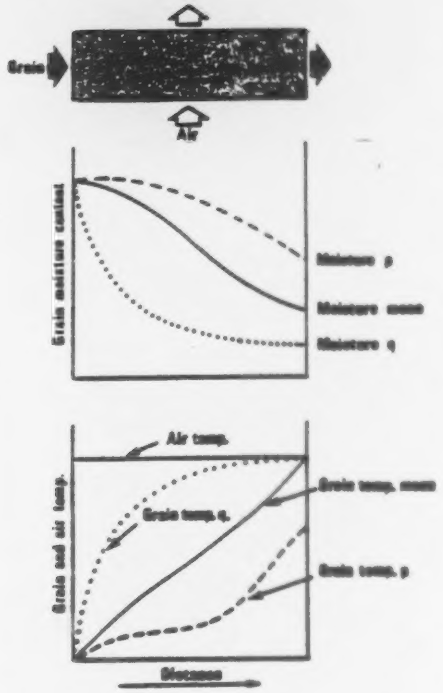

Grain
Air
Grain moisture content
Moisture p
Moisture mean
Moisture q
Air temp.
Grain and air temp.
Grain temp. q
Grain temp. mean
Grain temp. p
Distance

Fig. 2.7. Schematic of a continuous-flow crossflow grain dryer showing the moisture and temperature gradients in the dried grain.

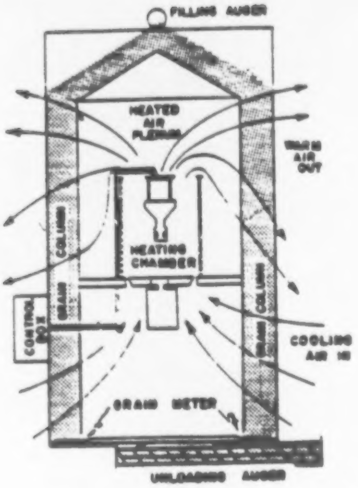

FILLING AUGER
HEATED AIR PLENUM
WARM AIR OUT
GRAIN COLUMN
HEATING CHAMBER
GRAIN COLUMN
CONTROL BOX
COOLING AIR IN
GRAIN METER
UNLOADING AUGER

Fig. 2.8. Crossflow grain dryer in which the cooling air is recycled, and a reversal of airflow takes place.

er in the grain columns is a less expensive (although less effective) solution to the problem of the large moisture gradient. This unit turns the over-heated grain at the air-inlet side to the air-exhaust side of the column, and thus minimizes overheating (Otten et al.,1980). Crossflow corn dryers without air-reversal or grain inverters have gradients across the drying column as large as 20% in moisture content and 50% in grain breakage (Gustafson et al.,1981).

Two new features have recently been added to the basic crossflow design, differential grain-speed and tempering. Both features improve grain-quality (Kuppinger,1980). Differential grain-speed refers to the design in which grain closest to the air-inlet side is moved at a faster rate through the column than grain at the air-exhaust side, in order to decrease the moisture and temperature differentials across the column. Tempering is the process of interrupting the grain-drying process in order to decrease the temperature and moisture gradients in the kernels before subsequent final drying. A crossflow dryer incorporating air-recycle, air-reversal, differential grain-speed, and tempering is commercially available in the United States (Bakker-Arkema et al.,1982); its high initial cost is preventing general acceptance.

Crossflow corn dryers operate at 80-110°C and 80-110m^3/min t.

Mixed-Flow Dryers

Mixed-flow dryers are also called cascade or rack-type dryers. Grain is dried in mixed-flow dryers by a mixture of crossflow, concurrent-flow and counterflow drying processes. The grain flows over a series of alternate inlet and exhaust air ducts (see Fig. 2.9). This results in a fairly uniform drying treatment of the grain kernels, and therefore in a relatively uniform moisture content and quality of the

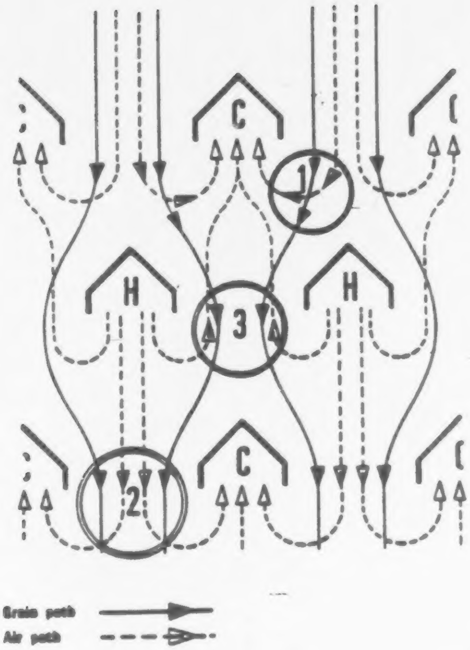

C
C
H
H
1
3
2
Grain path
Air path

Fig. 2.9. Mixed-flow grain dryer.

H = Hot air inlet duct.
C = Cold air exhaust duct.
1 = Area of crossflow.
2 = Area of concurrent-flow.
3 = Area of counter-flow.

dried grain (Mühlbauer,1987).

The drying-air temperature in mixed-flow dryers is higher than in crossflow dryers since the same grain is not subjected to the high drying temperature for as long in the mixed-flow dryer.

Mixed-flow dryers are more expensive to manufacture than crossflow dryers, and require more extensive air-pollution equipment. For these reasons, the number of mixed-flow dryer manufacturers has decreased in the United States notwithstanding the excellent grain-quality characteristics of the mixed-flow dryer type. Elsewhere in the world, mixed-flow dryers remain the predominant large continuous-flow dryer type.

Two West European mixed-flow grain dryer manufacturers have in the past year entered the United States market in response to the "grain-quality" problem (Cimbria,1987; Law,1987).

Mixed-flow corn dryers operate at 110-130°C and 60-70m^3/min t.

Concurrent-Flow Dryers

In a concurrent-flow (CCF) dryer, the grain and drying air flow in the same (vertical) direction through the dryer. The grain is cooled in a counterflow cooler in which the grain and air flow in the opposite directions. A commercial CCF dryer consists of two or three concurrent-flow drying zones and one counterflow cooler. A tempering zone separates two adjoining drying beds. Fig. 2.10 illustrates a two-stage CCF dryer.

The most distinguishing feature of concurrent-flow drying is the uniformity of the drying process (see Fig. 2.11). Every kernel undergoes the same heating/drying/cooling process in a concurrent-flow dryer unlike in the crossflow and mixed-flow dryers. Therefore, no kernel is

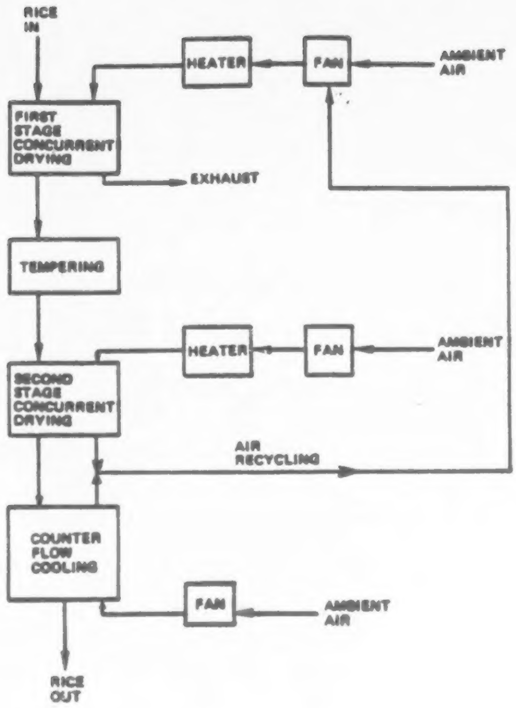

RICE IN
HEATER
FAN
AMBIENT AIR
FIRST STAGE CONCURRENT DRYING
EXHAUST
TEMPERING
HEATER
FAN
AMBIENT AIR
SECOND STAGE CONCURRENT DRYING
AIR RECYCLING
COUNTER FLOW COOLING
FAN
AMBIENT AIR
RICE OUT

Fig. 2.10. Two-stage concurrent-flow grain dryer with counterflow cooler and one tempering zone.

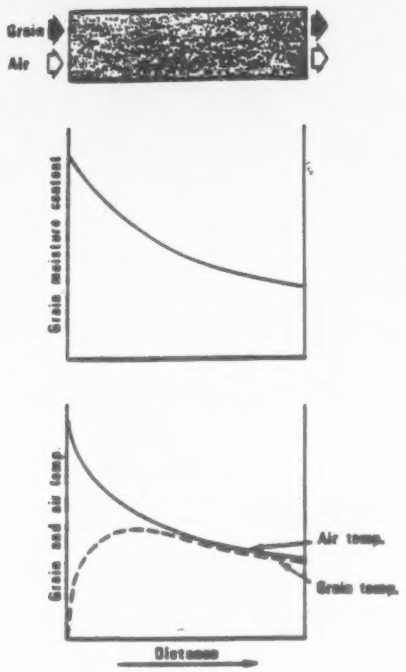

Grain
Air
Grain moisture content
Grain and air temp.
Air temp.
Grain temp.
Distance

Fig. 2.11. Schematic of a concurrent-flow grain dryer showing the uniform moisture content and temperature of the dried grain.

over-heated and overdried in a properly designed and operated concurrent-flow dryer (Dalpasquale,1981). In the counterflow cooler of a CCF dryer, the hot grain exiting the last drying zone is subjected to a gentler cooling process than in the other dryer types, since the largest temperature difference between the cooling air and the warm grain kernels is never more than 5-10°C.

The drying air temperature in a CCF dryer is much higher than in other grain dryer types because the wet grain is subjected to the hot drying air not for a period of hours (as in some crossflow dryers), or minutes (as in mixed-flow models), but only for a period of seconds. Thus, the grain does not approach the temperature of the drying air as in the other two dryer types. For instance, in the concurrent-flow drying of corn, the maximum kernel temperature is only 80°C for a period of less than three seconds although the drying-air temperature is 275°C (Bakker-Arkema et al.,1984).

The uniform and relatively gentle drying and cooling of the grain in CCF dryers results in dried grain of superior quality compared to that dried in other continuous-flow dryer types (Table 2.7). The breakage susceptibility increase of CCF-dried corn is one half that of mixed-flow and one fourth that of crossflow-dried corn.

Concurrent-flow corn dryers operate at 175-285°C and 40-60m^3/min t.

Overseas Drying Systems

Much of the grain in the developing world is sundried. Sundrying is the process in which wet grain is spread on the ground in the open air in 10-20cm deep layers, stirred manually periodically, covered during rainy periods, and slowly dried to 12-14% moisture content. Sundrying is common for rice in south-east Asia, and for corn, wheat

Table 2.7. The effect of dryer type on the drying-air temperature, the maximum grain temperature, and the breakage susceptibility of corn being dried from 25 to 15%.

Dryer Type	Drying-air Temp (°C)	Max. Grain Temp (°C)	Breakage Susceptibility (%)
Crossflow	80-110	80-110	20
Mixed-flow	100-130	70-100	10
Concurrent-flow	175-285	60-80	5

Sources: Kuppinger(1980), Mühlbauer et al.(1979), Nellist(1982), Rodriguez(1982) and soybeans in China and Russia. Sundrying is a labor-intensive, low-capacity and high-cost process but can produce excellent quality grain if the weather conditions are favorable and the operators are knowledgeable (Bengtsson and Whitaker,1986).

In many countries (e.g. China, Nigeria) corn is dried on the ear in corn-cribs (Bengtsson and Whitaker,1986). This slow drying, low-capacity drying process can produce dried corn of superior quality. It is not practical to re-introduce corncribs in the United States on a large scale. A small market does exist in the United States for ear-corn (Anderson,1987).

As mentioned in this chapter previously, mixed-flow grain dryers are common in the major grain-producing countries outside of the North-American continent. They are preferred over crossflow dryers mainly because of their (perceived) ability to produce better quality grain (Nellist,1982). The major manufacturers of mixed-flow dryers are located in Brazil, Denmark and France. Each company exports aggressively, so that mixed-flow dryers are in use all over the world.

During a recent (5/87) grain-depot inspection trip through China (a major competitor of the United States in the corn and rice markets), the author observed two "new" off-farm grain drying types, the rotary dryer and the fluidized bed dryer. Both produce excellent quality grain; the designs were unsuccessfully test-marketed in the United States in the sixties. A new look at these dryers for U.S. conditions appears justified.

CHAPTER 3

AUXILIARY EQUIPMENT INTERACTIONS

Relevant interactions with the grain drying process to be considered in this chapter include harvesting, cleaning and handling/transportation. Harvesting precedes the drying process, cleaning and handling/transportation is carried out either before and/or after drying.

Harvesting

The optimum moisture content to minimize losses during harvesting differs for the different grains. For corn it is 28-32%, for soybeans 18-22%, and for wheat 18-20%. At higher moisture contents, the grain kernels often rupture during the combining process, at lower MC values they often crack. In addition, the percentage of broken kernels and foreign material (BCFM) in the combined grain is high when it is harvesteded outside the optimum MC range.

Quantification of the kernel rupturing and cracking during the grain harvesting process is documented in the OTA reports by Paulsen (1987) and Schrock(1987).

Cleaning

Grain-dryer manufacturers invariably recommend the cleaning of the wet grain before drying. [Cleaning of the grain after drying is recommended to improve the storability of the grain; dryer manufacturers seldom comment on the desirability of post-cleaning].

Cleaning of the grain before it reaches the dryer has the following advantages (Regge and Minaer,1979): (1) it results in a more uniform airflow in the dryer, and thus a more uniform moisture content (and quality) of the dried grain, (2) it decreases the static pressure (the airflow resistance) of the grain, and thus increases the airflow rate and the dryer capacity, (3) it eliminates the drying of material which deleteriously affects the final quality of the grain, and (4) it results in less air-pollution. Obviously pre-cleaning also has disadvantages: (1) it requires additional investment (of a cleaner), (2) it requires the handling of wet BCFM, (3) it requires the rapid sale of wet, easily-molding material, and (4) it results in a limited dry matter loss.

Although the advantages of pre-cleaning wet grain are fairly well understood by dryer operators, most do not pre-clean [and many do not post-clean either]. The quality of the United States grain crop would improve substantially if the grain industry would increase its pre- and post-cleaning practices (Gilbert,1986).

Grain cleaning is discussed in detail in the OTA report by Hurburgh (1987).

Handling/Transportation

The effect of handling/transportation actions on grain quality depends greatly on the grain moisture content, and to a lesser extent on the grain temperature (Kusterman and Kutzbach,1981; Paulsen,1983). Thus, the handling/transporation before and after drying should be considered separately.

At the time of harvest, grains usually have a moisture content and temperature at which the kernels are quite resilient (Scherer,1978). Handling and transportation prior to drying, therefore, do not contribute materially to the increase in breakage, stress-cracks and BCFM.

After the drying process, the grain kernels may have lost their resilience and have become brittle. Thus, it is after the drying process that the handling and transportation actions may become critical, and excessive handling and long transportation hauls may result in kernel breakage and grain-quality loss. A gentle drying process will not cause stress-cracking, and therefore the subsequent kernel breakage and grain-quality loss will not occur.

The effect of handling/transportation on grain quality is considered in the OTA report by Baumel(1982).

CHAPTER 4

DRYER PERFORMANCE FACTORS

The performance of a grain dryer is affected by a number of factors. They fall into four main categories: (1) physical, (2) biological, (3) economic, and (4) human. Each one can be the controlling factor on the grain-quality performance of a drying-system.

Physical Factors

The main physical factors affecting dryer performance are the climate and the weather.

The climate determines the type of hybrids which can be grown in a particular region, and the expected moisture content range and weather conditions at the time of harvest. The hybrid-effect is discussed in the next section. The initial moisture content of the grain in a dryer has a significant affect on dryer performance. Not only are the capacity, the energy consumption, and operating costs of a dryer influenced by the initial moisture content of the grain, but the grain quality is also affected by its moisture content. In general, if grains are harvested above or below the optimum harvest moisture content, the grain-quality loss in the subsequent drying process is increased (Brooker et al.,1974). Thus, in some northern states in the United States (e.g. Michigan, Wisconsin) where harvest moistures frequently exceed the optimum value, the grain-quality of the corn and soybean crops is inherently inferior to that of grains grown in the central cornbelt states (e.g. Illinois, Iowa). Judicious hybrid selection can partially but not totally offset this grain-quality difference.

Weather is the second physical factor influencing dryer performance. Certain years will be wet in the summer and fall, and result in excessively high moisture content of the grain reaching the dryer. As explained in the previous paragraph, this leads to low dryer capacity, high energy consumption, high drying cost, and decreased grain-quality. The weather conditions have a direct effect on the performance of some on-farm bin-dryers; the low-capacity drying systems (i.e. natural-air, solar) may not be able to dry wet grain before molding sets in (Silva, 1980). Off-farm systems are less directly affected by weather conditions.

Biological Factors

Two biological factors affect dryer operation, the grain type and the genotype.

The drying properties of grains and oilseeds are dependent on grain type (Bakker-Arkema et al.,1983). Of the three seeds considered in this report -- corn, soybeans, and wheat -- wheat dries most rapidly, corn most slowly. This is illustrated in Table 4.1 for corn and wheat; a concurrent-flow dryer has a 23% higher throughput for wheat than for corn, although operating at the same drying-air temperature. Also, the maximum grain temperature of the corn is substantially higher than of the wheat,thus affecting the quality change of the two grains differently. Finally, note that the energy use of a dryer is affected by grain type.

The genotype determines the drying rate of single corn kernels (Stroshine et al.,1986); some genotypes can be considered slow drying types, others fall in the fast-drying category. In general, the new genotypes dry more rapidly than those being grown ten years agc (Li and Morey,1984). The dryer capacity and fuel efficiency of a dryer are higher with the new than with the old genotypes. The drying rate

Table 4.1. Drying performance of corn and wheat in a two-stage concurrent-flow dryer at constant power requirement and moisture removal; drying air temperature 150°C.

Parameter	Corn	Wheat
Power (HP/m^2)	1.8	1.8
ΔM (% w.b.)	6.0	6.0
Airflow (m^3/m^2min)	38.1	28.3
Static Pressure (kPa)	2.1	2.9
Throughput (kg/m^2h)	1500	1850
Θ_{max} (°C)*	75	65
Θ_{out} (°C)**	56	39
Energy Use (kJ/kg)	4867	2911

*Θ_{max} is the maximum grain temperature occurring in the dryer.

**Θ_{out} is the temperature of the grain exiting the second drying stage.

Source: Bakker-Arkema et al.(1983)

of wheat and soybeans is not influenced by genotype (Nellist,1985).

Not only is there a difference in drying rate among corn genotypes, the breakage susceptibility after drying also varies among them (Stroshine et al.,1981; Paulsen et al.,1983). As the data for four genotypes in Table 4.2 shows, a five-fold increase in breakage susceptibility may occur when switching genotype.

Economical Factors

Economics can affect dryer performance through its influence on fuel prices and fuel availability.

The relative price of natural gas, fuel oil, liquid propane (LP), and electricity per 10^6 kJ changes from year to year. At present (8/1987), natural gas is the least expensive and electricity the most expensive energy source in the United States; for this reason, most large U.S. commercial dryers employ natural gas.

In the mid-seventies, there was a shortage in fossil fuels in the United States during several drying seasons; as a result, some farmers turned to biomass fuels as a heat source for their drying systems (Mwaura et al.,1982). In some countries (e.g. China, Brasil), fossil fuels are in such short supply or are so high in cost, that alternative fuel sources have to be employed in grain drying systems. Coal, straw, wood and rice hulls are among the most commonly used biomass materials (Blakeman,1982).

Fuel-type affects dryer operation because it influences the burner (or furnace) efficiency and the drying-air quality. In the United States, grain dryers are directly heated; overseas, indirect heating of grain drying systems is common to prevent adsorption of polycyclic aromatic hydrocarbons (contained in the drying air) by the grain (Hutt and

Table 4.2. Breakage susceptibility of different corn genotypes after hand-shelling and drying at 24°C.

Genotype	Breakage Susceptibility (%)
FRB 73 x FR 18	23.5
FRB 73 x PA 91	10.5
FRB 73 x FR Mo 17	7.5
FR Mo 17 x FR 634	4.3

Source: Paulsen et al.(1983)

Winkler,1978). Indirect heating is accomplished through the use of heat exchangers; it is less energy efficient, more costly, and less grain-pollutant than direct heating (Anderson et al.,1983).

Of the three fossil fuels commonly used in directly-heated dryers in the United States (i.e. natural gas, fuel oil, LP), only fuel oil causes hydrocarbon adsorption by the grain (Hutt and Oelschläger,1976).

Human Factors

The drying of grain is a complicated heat/mass/momentum transfer process of a heat-sensitive biological product. It is frequently not well understood by the average dryer operator. Indirectly, this leads to the human-factor effect on dryer performance.

At most United States grain elevators, the job of dryer operator is seasonal; it requires usually 12-hours per day, 7 days per week attendance for a 2-3 months period. The pay rate is marginal, and the job-training is usually by trial-and-error. Therefore, it is not surprising that dryer maintenance, dryer supervision, and dryer operation are far from optimum. All these factors affect the performance of the typical elevator grain dryer with respect to capacity, energy efficiency and grain quality (Bakker-Arkema,1985). The most frequently made mistake is the use of excessively high drying temperatures in order to increase dryer capacity.

Although dryer operation on United States farms appears to be more expert, it is dependent on the human factor also for the same reasons as stated in the previous paragraph.

Auxiliary Factors

Several auxiliary-equipment (e.g.instrumentation) items influence the performance of a grain dryer. Included in this category are the grain moisture meter, the air temperature meter and the dryer-controller. [The effect of the cleaning and the grain-handling equipment on dryer performance is discussed in Chapter 3].

Moisture meters are an integral part of a grain drying system. Electronic meters are universally used at U.S. grain processing facilities. The accuracy of the meters commercially available has recently been investigated (Hurburgh and Hazen, 1984); an accuracy of ± 1% in the low (13-16%) moisture content range and of ± 2.5% in the high range is typical even for recently calibrated meters. This situation contributes substantially to the overdrying and underdrying (and thus, quality loss) of the United States grain crop. Improved moisture-meter design and calibration should be a top research priority of the grain industry.

Air-temperature measurement in a grain dryer is usually by means of a single thermocouple or thermistor. This practice is acceptable if the temperature distribution in the plenum of a grain dryer is uniform. This is not the case in many off-farm dryers (Anderson, 1985) nor in on-farm models (Silva, 1980); temperature differences of 20-35°C in the plenum are not unusual. This condition results in overheating of part of the grain column, and deterioration of the average grain quality.

The control of grain dryers is usually manual; overdrying is frequently the result (see Fig. 4.1). Automatic control systems have recently become commercially available for in-bin and continuous-flow grain dryers (Eltigani, 1987); their use leads to a saving in energy and drying costs, and limits the degree of overdrying (see Fig. 4.2) and quality deterioration. Minimizing the degree of overdrying (and overheating) is highly beneficial to the grain crop (see Chapter 2).

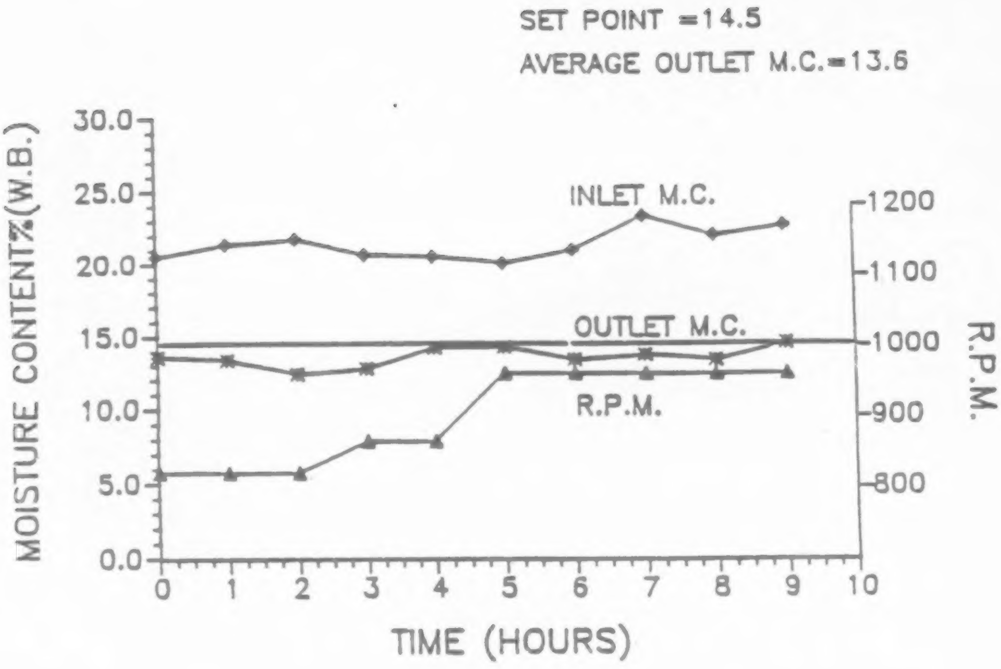


Figure 4.1. Manually controlled dryer; inlet and outlet moisture contents (% w.b.), and auger rpm over a 9-hour period (Source: Eltigani, 1987).

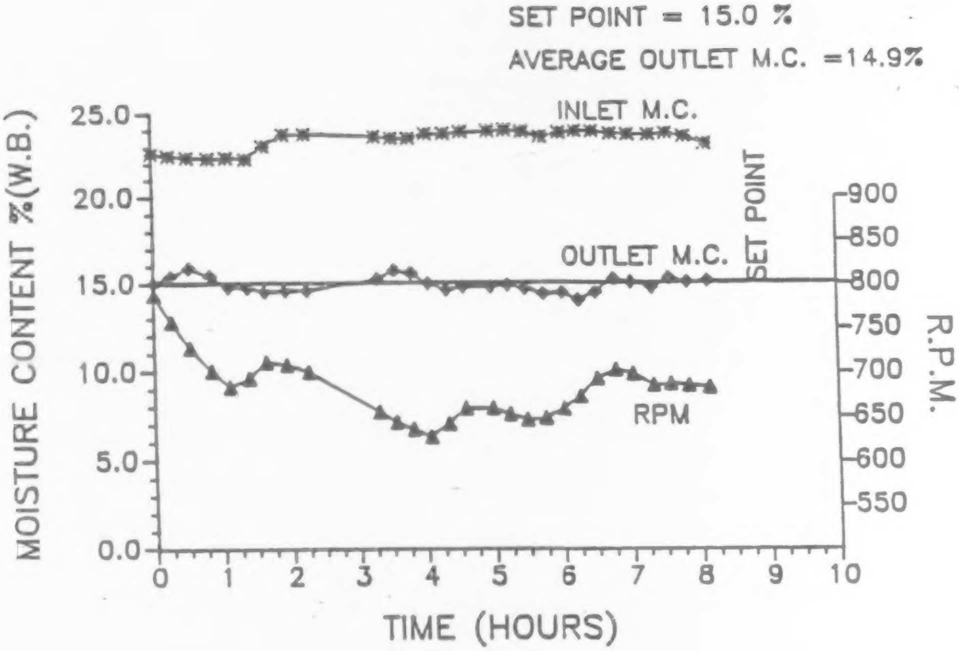


Figure 4.2. Automatically controlled dryer; inlet and outlet moisture contents (% w.b.), and auger rpm over an 8-hour period (Source: Eltigani, 1987).

CHAPTER 5

DRYER EFFECT ON GRAIN QUALITY

As noted in the Introduction, the process of drying has a greater influence on grain quality than all the remaining grain-processing operations combined (Hamdy et al.,1977). Thus, if grain of superior quality is to be produced, it is imperative to optimize the dryer type and the dryer operating parameters with respect to grain quality. These two effects will be considered in this chapter.

Dryer Type

The different grain drying systems in use in the United States are discussed in Chapter 2. In general, in-bin systems are low-temperature units employed on farms; continuous-flow systems are high-temperature models used at on-farm and off-farm locations.

A number of on-farm comparative drying studies have been conducted with corn in the Midwest to evaluate the effect of dryer type on grain quality. Table 2.6 shows the results from one of these investigations: combination-drying systems produce corn of better quality (i.e. with fewer stress-cracks, and lower breakage susceptibility) than high-temperature batch dryers. Similar results have been obtained by other researchers for other types of on-farm high-temperature dryers (Foster and Peart,1976; Morey et al.,1981).

The consensus among investigators is that corn can be dried in high-temperature batch or continuous-flow dryers to 18-21% without greatly affecting the grain quality (except for viability). However, below this moisture range, a low rate of drying is recommended if optimum grain quality is desired. The second stage of drying can be natural-air or low-temperature in-bin drying with or without the use of grain stirrers.

Tempering of the partially dried grain before the second drying operation always has a beneficial effect on grain quality (Gustafson et al.,1983).

The effect of off-farm dryer type on grain quality has been investigated in a comparative study of crossflow and concurrent-flow corn drying (Gygax et al.,1974). It was established that the average breakage susceptibility increase of crossflow dried corn is twice that of concurrent-flow dried material. The superior grain quality characteristics of concurrent-flow grain drying compared to crossflow drying have also been reported by Thompson(1979), Mühlbauer et al.(1979), Hall and Anderson (1980), and Nishiyama(1987). The uniform heat treatment of the grain in a concurrent-flow dryer, and the lack of extensive overheating of part of the grain (as occurs especially in crossflow dryers), are responsible for its minimum decrease in grain quality.

No direct comparison has been made of commercial crossflow and mixed-flow grain dryers with respect to grain quality. Researchers agree, however, that mixed-flow dryers are able to produce grain with fewer stress-cracks than crossflow models (Nellist,1983). Food-grain processors, therefore, prefer mixed-flow dryers over crossflow dryers (Frito-Lay, 1987).

The breakage susceptibility ratio of corn in concurrent-flow, mixed-flow, and crossflow dryers is about 1:2:4 (see Table 2.7).

Dryer Operating Parameters

The main dryer operating parameters affecting grain quality are the air temperature, the grain velocity, and the airflow rate (Strehler, 1975). A dryer operator is able to adjust the first two parameters on every grain dryer, and on some units all three. Collectively, the three parameters determine the drying rate and the maximum grain temperature of a lot of grain being dried, and thus establish the quality of the dried lot.

An example of the effect of air temperature on breakage susceptibility is given in Table 5.1 for the drying of corn in an in-bin continuous-flow dryer; note that the energy consumption is also affected by the drying-air temperature. Similar information on crossflow dryers was obtained by Gustafson and Morey(1979).

Table 5.1. The effect of drying-air temperature on the energy use and the breakage susceptibility increase of corn dried in an in-bin counterflow drying system.

Air Temp (°C)	Breakage Susceptibility Increase (%)	Energy Use (kJ/kg)
93	11	5105
82	5	4500
49	3	4385

Source: Kalchik et al.(1981)

CHAPTER 6

NEW AND EMERGING DRYING TECHNOLOGIES

Among the new and emerging drying technologies, some have the potential to have a significant impact on the overall quality of the United States grain crop, especially the corn crop. Several have already been discussed in previous sections, others have not yet been mentioned because of their incomplete development, their high initial cost, or their overseas patents.

Combination drying has been shown in Chapter 2 to improve corn quality at the farm level. Although the procedure has been known for a decade, it is still used only sparingly because the more demanding logistics and the additional grain-handling requirement. No promising new drying technology appears to be on the horizon for on-farm grain drying.

Mixed-flow and concurrent-flow drying are off-farm drying technologies which produce improved grain quality compared to the standard crossflow drying process. Both dryer types are commercially available in the United States. Their high initial cost (10-20% more than of comparable crossflow dryers) has thus far prevented their market penetration. The same can be said of automatic moisture controllers. If the payback period of these technologies can be shortened through a price increase of high-quality grain, rapid market penetration can be expected.

Two off-farm grain dryers not used in the United States, but recently inspected by the author (FWBA) in China, are the fluidized-bed dryer (see Fig. 6.1) and the cascading-rotary dryer (see Fig. 6.2). Both types are employed on a limited basis for the drying of rough rice, and both were found to produce a high quality product. A fluidized-bed grain dryer was at one time commercially available in the United States, but pro-

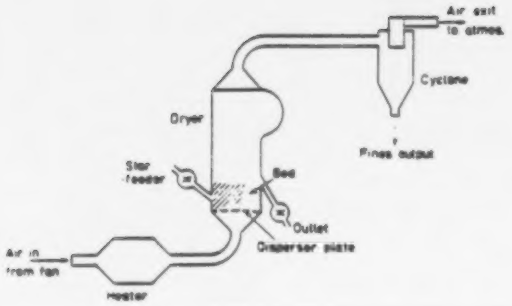
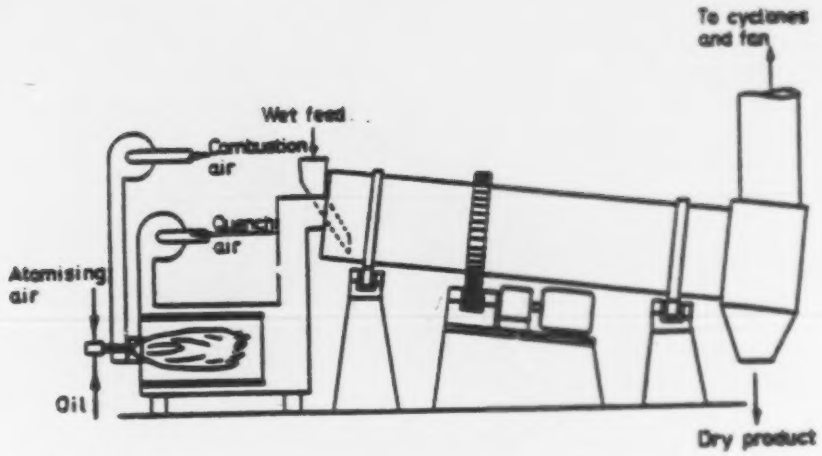

Air exit
to atmos.
Cyclone
Dryer
Fines output
Star
feeder
Bed
Outlet
Disperser plate
Air in
from fan
Heater

Fig. 6.1. Fluidized-bed grain dryer.



To cyclones
and fan
Wet feed
Combustion
air
Quench
air
Atomising
air
Oil
Dry product

Fig. 6.2. Cascading-rotary grain dryer.

duction was discontinued due to the high electrical power-costs and the excessive air-pollution; the spouted-bed dryer is a special form of the fluidized-bed dryer (Ghaly et al.,1974). The cascading-rotary dryer is used in the United States grain processing industry for the drying of parboiled rice. High initial cost, high maintenance cost, and high energy consumption are characteristics of U.S. rotary dryer designs; the same can be said of the Canadian rotary grain dryers which mix heated solids with the grain (Tessier and Raghaven,1984). It appears, based on the Chinese experiences, that U.S. dryer designers should reconsider fluidized-bed and cascading-rotary dryers as possible dryer designs for the United States market.

At least two U.S. firms (i.e. McDonnell-Douglas, Aeroglide) have experimented with micro-wave grain dryers in the eighties. Both companies have marketed commercial models without success. The advantages of low energy consumption and of high grain quality were offset by high initial cost and low product throughput. It is unlikely that microwave grain drying can compete with conventional grain drying techniques as long as the economic return of improved grain quality remains low.

CHAPTER 7

IMPACT OF GRAIN-QUALITY DEPENDENT PRICING ON DRYER DESIGN

If the price of corn was based on quality (i.e. breakage susceptibility and number of stress cracks), and the differential in price between high quality and low quality grain was in the range of 10-30 cents per bushel, the U.S. grain processing industry (i.e. farmers and elevator operators) would produce higher quality grain with current drying technology. Farmers would expand their low-temperature and combination drying facilities, and elevator managers would operate their crossflow dryers at lower temperatures. The number of "10-30 cents per bushel" represents a consensus value reached by industry/government/academic personnel participating in the USDA NC-151 workshop entitled "Relating Grain Quality to End-Use Value", held at Ames, IA, July 15-17, 1987.

A 10-30 cent per bushel grain quality premium will lead to rapid market penetration of the emerging technologies of mixed-flow and concurrent-flow drying at the elevator level. Likewise, the adoption of automatic controllers on large-scale dryers would be rapid. [In Ontario, Canada, a government subsidy of $30,000 per elevator facility has resulted within a few years in the installation of the controllers at a majority of the elevators.] A substantial quality premium is also likely to lead to the development by U.S. dryer manufacturers of such new designs as the fluidized-bed dryer and the cascading rotary dryer. Microwave grain dryers are unlikely to be impacted by grain-quality dependent pricing unless the corn price doubles or triples.

It is unclear to the author what the impact of grain-quality pricing will be on the design of soybean and wheat dryers.

CHAPTER 8

SHORT- AND LONG- TERM RESEARCH NEEDS

Quantification of the grain-quality characteristics of the new and emerging drying technologies discussed in Chapter 6, is the first short-term research need. Recent funding of this type of research by U.S. government agencies has been scarce due to the applied nature of such investigations. Unfortunately, industrial and commodity-group support for grain-quality research has also been limited.

Quantification of the grain-breakage characteristics of the most popular corn and soybean genotypes grown commercially in the different production areas of the United States, is a second short-range research need. Except for the Indiana and Illinois regions, no research has been conducted on this subject.

Short-term equipment-related research needs include:

(1) Confirmation of the favorable grain-quality characteristics of the differential grain-speed crossflow dryer.

(2) Quantification of the grain-quality improvement of dryers operating under automatic control.

The following long-range grain-drying research projects will have an impact on the end-quality of United States grain:

1. Optimization of the mixed-flow dryer design, in particular of the airflow patterns, the anti-pollution devices, and the air-temperature/grainflow/grain-quality relationships, for U.S. conditions.
2. Fine-tuning of the concurrent-flow dryer design, in particular of the grainflow uniformity, the pre-cleaning requirements, and

the grain-temperature distribution in the tempering zones.

3. An analytical and pilot-scale investigation of the fluidized-bed drying of grain.
4. An analytical and pilot-scale investigation of the cascading-rotary drying of grain.
5. An economic investigation of microwave grain drying.

The annual costs of the short- and long- term research needs are in the $2-3 million range.

The research needs (and expected changes) in the grain harvesting, handling, storage and transportation operation, resulting from adoption of the new drying technologies discussed in Chapters 6 and 7, are minor. At most, the new dryers may require improved pre-cleaning of the grain.

CHAPTER 9

IMPACT AND COST OF NEW DRYING TECHNOLOGIES

Since it has been established that the deterioration of grain quality occurs mainly during the drying process [at least of corn], general adoption of the new and emerging drying technologies will have a significant impact on the quality of the major U.S. crop (i.e. corn), and to a lesser degree on the wheat and soybean crops. The author estimates that the average breakage susceptibility of the U.S. corn and soybean will be halved.

Cost of implementation of the new drying technology is estimated to be moderate. The price increase in the initial cost of the drying equipment is estimated to fall in the 10-15 percent range. The total annual additional costs to the U.S. economy are not expected to exceed the 10-20 million dollar range for gradual adoption of the new technologies.

CHAPTER 10

SUMMARY

The drying step is a critical operation in the harvesting/drying/storage/transportation of grains if a product of high quality is to be produced. It is generally agreed that drying is the major cause of grain deterioration in this sequence. Of particular concern is the increase in breakage-susceptibility of corn and soybeans, and the decrease in the milling quality of wheat. The artificial drying of wheat and soybeans is not frequently required. Therefore, this report mainly considers the drying of corn.

A large amount of water is evaporated from the grain in the drying process; per metric ton of corn, over 100 kg of water is removed in drying the crop from 25 to 15% moisture content, requiring over 500,000 kJ at a cost of about $2.50 (at 1987 energy prices). Over 80% of the U.S. corn crop is dried on farms, less than 5% at local elevators or terminals.

Although the grain-drying process is the major culprit in lowering the average quality of the U.S. corn crop (and to a lesser degree of the soybean crop), and although newly-developed drying technology minimizes grain-quality deterioration, the application of the new dryer designs and systems can not be justified by the U.S. grain producers and handlers until they are compensated by a higher selling price.

On-Farm Drying

On-farm dryers fall into three categories -- bin, non-bin, and combination dryers. Bin dryers are in general low-capacity, low-temperature systems, able to produce excellent quality grain. Non-bin dryers, the most popular dryer type in the U.S., are high-capacity, high-temperature systems which frequently overheat and overdry the grain, and thereby cause serious grain-quality deterioration. Combination drying combines the advantages of both systems (i.e. high capacity and high quality) but requires additional investment, and is logistically more complicated. A switch by farmers from non-bin drying to combination drying would result in a significant improvement in the quality of the U.S. corn crop.

Off-Farm Drying

Off-farm or elevator dryers fall into three classes -- crossflow, concurrent-flow, and mixed-flow dryers. Off-farm dryers are high-capacity, high-temperature units. In the U.S., crossflow models are the most prevalent; they dry the grain non-uniformly, causing excessive stress-cracking of the grain kernels. Mixed-flow dryers are common in other major grain-producing countries; the grain is dried more uniformly in these dryers, and is usually of higher quality than that dried in crossflow models. Concurrent-flow dryers have the advantage of producing the best quality grain; their disadvantages are the relatively high initial cost and the newness of the technology. A change at the elevator level from crossflow to mixed-flow/concurrent-flow dryers will beneficially affect the quality of the U.S. grain crop. A significant improvement in grain quality can also be obtained by optimizing the dryer operating-parameters (i.e. the air-temperature/airflow/grainflow settings) of existing cross flow dryers, by selecting the best grain genotypes, and by installing automatic dryer controllers.

New And Emerging Technologies

It is estimated that application of existing drying technology is able to decrease the breakage susceptibility of the U.S. grain crop by

50%. Several new and emerging technologies have the potential to further decrease the grain deterioration level by another 50%. Among these are differential grain-speed crossflow drying, multi-stage concurrent-flow drying, multi-stage mixed-flow drying, fluidized-bed drying, and cascading-rotary drying. Research of these drying techniques for U.S. conditions is recommended. A grain-quality premium of 10-30 cents per bushel of grain is believed to be necessary for the new and emerging technologies to be generally accepted. The annual additional cost of implementing the new technologies gradually is estimated to fall in the 10-20 million dollar range.

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APPENDIX

GLOSSARY

Aeration - the slow cooling of grain in storage to within 3-5°C of the average daily ambient temperature.

Airflow - the flow of air through a volume of grain; usually expressed in m^3 per sec per tonne of grain.

Air-recycle - the process of re-using part of the exhaust air in a high-temperature continuous-flow grain dryer in order to improve the energy efficiency.

Air-reversal - the process of reversing the direction of the airflow in a crossflow grain dryer in order to decrease the moisture gradient in the drying column.

Batch-in-bin dryer - a high-temperature bin dryer in which a batch of grain is dried in a relatively thick layer (0.6-1.0m) at an air-temperature of 45-60°C, and is cooled with ambient air.

Bin drying - the drying of grain in a bin which is provided with a perforated floor (or air ducts), and a fan/heater combination.

Biomass fuel - a fuel from naturally grown material (e.g. wheat straw, corn stover, corn cobs and wood chips).

Breakage susceptibility - the breakage likely to occur in a lot of grain as it moves through the processing/marketing chain; determined with a grain breakage tester, and expressed in the percentage of grain passing through a 12/64 inch screen.

BCFM - broken corn and foreign material that passes through a 12/64 inch screen.

Combination drying - drying of grain (usually corn) from harvest moisture to an intermediate moisture content (18-24%) in a high-temperature dryer, followed by final bin-drying with ambient air to 12-15%.

Concurrent-flow dryer - a continuous-flow high-temperature (120-260°C) grain dryer in which the drying air flows in the same vertical downward direction through the dryer as the grain.

Counterflow cooler -	a continuous-flow cooler in which the cooling air moves in a direction through the cooler opposite to the grain.
Crossflow dryer -	a continuous-flow high-temperature (70-110°C) grain dryer/cooler in which the drying air flows perpendicular to the vertical downward direction of the grain.
Differential grain-speed dryer -	a crossflow dryer in which the grainflow rate is higher at the air-inlet side of the grain-column than at the air-outlet side.
Direct heating -	the heating of drying air by the direct combustion of a fuel (i.e. fossil or biomass); the combustion products are mixed with the heated air.
Dryeration -	the combination drying process in which corn is dried in a high-temperature dryer to 16-18%, is tempered for 8-12 hours in a tempering bin, and is bin-dried to safe-storage moisture content with ambient air.
Energy efficiency -	the amount of energy required to evaporate water from the grain in the drying process; expressed in kJ per kg of water.
Fan -	a mechanical device for the propagation of a flow of air.
Fluidized-bed dryer -	a high-temperature continuous-flow dryer formed by a container partially filled with grain kept in suspension (i.e. a fluidized state) by high-velocity drying air.
Fossil fuel -	a fuel naturally produced from biological materials over a period of centuries (e.g. natural gas, oil, LP, and coal).
Grain cooling -	the cooling of grain to ambient temperature after the drying process.
Grain drying -	the removal of moisture from grain from harvest moisture content (18-35%) to safe-storage moisture content (12-15%); also called grain dehydration.

Grain inverter (turner) - a device placed in the grain-column of a crossflow dryer for turning the overheated/overdried grain from the hot air-inlet to the cold air-outlet side of the column, and the underheated/underdried grain from the air-outlet to the air-inlet side.

In-bin counterflow dryer - a high-temperature (60-80°C) bin dryer in which a partially dried 5-10cm layer of grain is removed semi-continuously from the bottom of the grain bed by a tapered auger; final-drying and cooling of the grain usually takes place in a second bin.

Indirect heating - the heating of drying air in a heat exchanger; the combustion products of the fuel are not mixed with the heated air.

In-storage layer-drying - a low-temperature (25-35°C) in-bin drying technique in which a bin is filled with successive layers (30-50cm) of wet grain after the previous layers have been dried to approximately the safe-storage moisture content.

Liquid propane (LP) - a fossil fuel frequently used in on-farm grain dryers.

Low-temperature drying - a form of bin drying in which the drying air is heated by 2-6°C above the ambient air temperature with an electric or liquid propane heater.

Microwave drying - a dryer in which the energy for evaporation of water is provided by microwave energy.

Milling quality - the quality of wheat and corn which expresses the baking and dry/wet milling characteristics, respectively, of the two grains.

Mixed-flow dryer - a continuous-flow high-temperature (80-120°C) grain dryer/cooler in which the grain flows over alternate inlet and outlet airducts; also called rack-type or cascade dryer.

Moisture gradient - the difference in moisture content in a crossflow dryer between the grain at the air-inlet and the air-outlet side of the grain column.

Natural-air drying - a form of bin drying in which the drying air consists of unheated ambient air.

Perforated floor - a grain-bin floor with 5-15% openings for air to pass through.

Plenum -	an air-chamber from which drying air is distributed through the grain being dried.
Portable batch dryer -	a portable high-temperature dryer in which a batch of grain is dried in a relatively thin layer (25-35cm) at an air-temperature of 60-115°C, and is cooled with ambient air.
Rotary dryer -	a high-temperature continuous-flow dryer consisting of a 1-6m diameter rotating drum in which the drying air and grain are introduced at one end of the drum, and are exhausted at the other end.
Solar collector -	a device to collect solar energy and convert it to heat for the warming of drying air.
Solar grain drying -	a form of bin drying in which the drying air is heated by 3-15°C above the ambient air temperature with the use of a solar collector.
Static pressure -	the resistance to the flow of air as it passes through a grain layer, an airduct, or a perforated floor; expressed in pascal per meter of grain.
Stress-cracking -	the development of hairline fissures in the grain (usually corn and soybeans) during handling and drying.
Sundrying -	the drying of a 5-15cm layer of grain spread out on the ground (or a concrete floor) in the open air.
Tempering -	the process in which partially dried grain is kept for a period of time (1-12 hrs) in a storage container without being subjected to a heat or mass transfer treatment.